7-1-2009

In-Plane And Out-Of-Plane Performance Of The Universal Building Products "Bullhorn" Connector

Clay Naito

Ruirui Ren

IN-PLANE AND OUT-OF-PLANE PERFORMANCE
OF THE
UNIVERSAL BUILDING PRODUCTS
EDGE CONNECTOR SYSTEM

By

Clay Naito, Ph.D., P.E.
Ruirui Ren

July 2009

ATLSS REPORT NO. 09-02

ATLSS is a National Center for Engineering Research
on Advanced Technology for Large Structural Systems

117 ATLSS Drive

Bethlehem, PA 18015-4729

Phone: (610)758-3525
Fax: (610)758-5902

www.atlss.lehigh.edu
Email: inatl@lehigh.edu

ABSTRACT

This report summarizes the in-plane and out-of-plane performance of the Universal Building Products Edge Connector (EC) system. The connector is intended for use as a flange-to-flange connection between precast concrete double tee panels or for connection between precast concrete wall elements. The connector was tested under monotonic in-plane shear and tension, and out-of-plane shear. The resulting capacities and associated damage are summarized in the report. This work was funded by Universal Building Products and was conducted at the ATLSS Research Center at Lehigh University.

Table of Contents

LIST OF FIGURES

BACKGROUND

The Edge Connector System produced by Universal Building Products is evaluated in two test series for load and deformation capacity. The connectors are sized for placement in 4-in. and 2-in. thick double tee flanges. As a means of assessing the displacement capacity and structural stiffness of the connections an experimental study was conducted. A subassembly consisting of the connector and a portion of the surrounding diaphragm was developed. Six connector types were examined in the first series, three are intended for 4in. flanges and the other three are intended for 2in. flanges. Two connector types were examined in the following series, and both connectors are intended for 4in flanges. All specimens were fabricated at full-scale. This report summarizes the experimental results of the Universal connectors tested under monotonically increasing in-plane tension, in-plane shear, and out-of-plane shear demands.

CONNECTOR DETAILS

The Edge Connector system consists of a hooked round bar and flat faceplate. The connector is fabricated in eight different configurations (Table 1). Three are fabricated from 0.5 in. diameter smooth bar, three from 0.625 in. smooth bar, one from #4 rebar, and one from #5 rebar. All specimens were fabricated at full-scale. Four of the six connectors are illustrated in Figure 1.

All connectors are welded to a slug plate PL4x1x3/8 using a ¼ filet weld 3.5 in. long. The welding details are illustrated in Figure 2. To allow for proper installation in a concrete panel a plastic former is used. The former is detailed to allow for expansion of the faceplate during welding, thus eliminating any concrete cracking. The plastic former is illustrated in Figure 3.

Table 1: Connection details

	Connector ID	Bar Type	Face Plate Height [in.]	Bar Diameter [in.]	Material
Test Series 1	A	Smooth	1.0	½	1018 Steel
	B	Smooth	1.0	½	304 Stainless
	C	Rebar	1.0	½	304 Stainless
	D	Smooth	1.5	5/8	1018 Steel
	E	Smooth	1.5	5/8	304 Stainless
	F	Rebar	1.5	5/8	304 Stainless
Test Series 2	G	Smooth	1.0	½	A36 Steel
	H	Smooth	1.5	5/8	A36 Steel

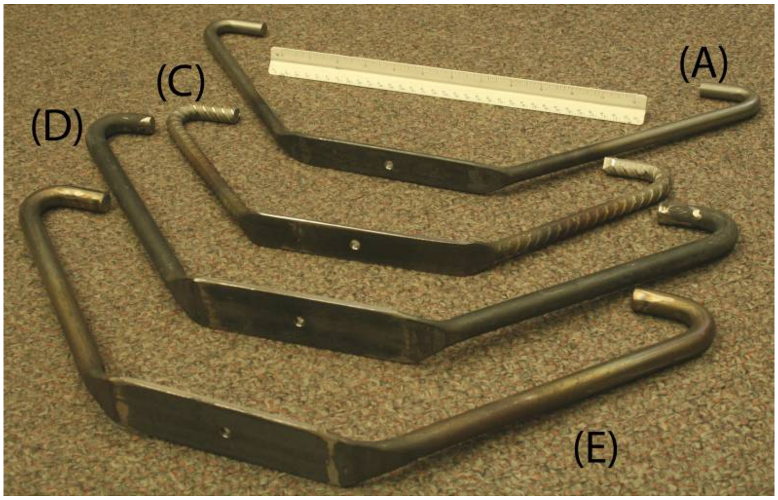


Figure 1: Connectors

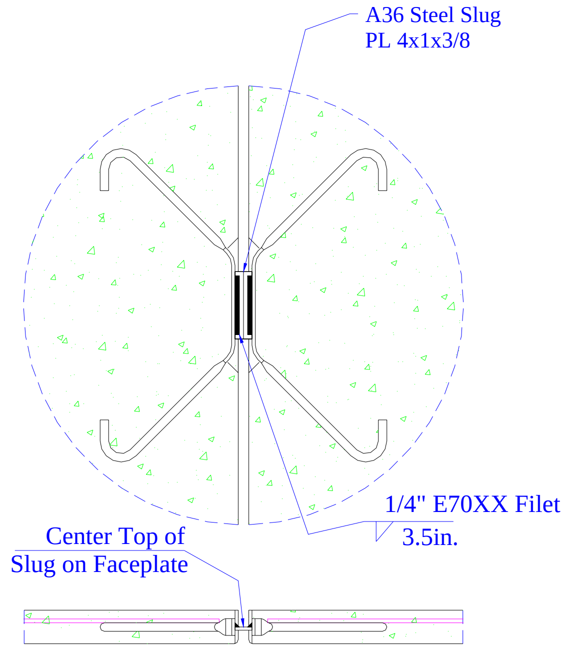


Figure 2: Welding details

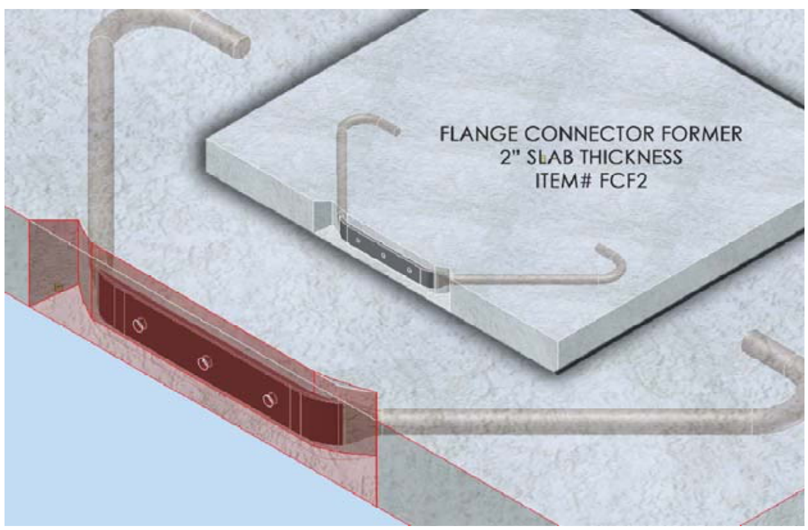


Figure 3: Plastic connector former

Material Properties

The compressive strength of the concrete used for the panels was measured when the connectors were tested in accordance with ASTM C39. The measured compressive strength was 5600+/-240 psi for the first series, and 6197+/-106 psi for the second series. The welded wire reinforcement and supplemental panel reinforcement meet ASTM A185, and A706 specifications. The connectors in the first series were fabricated from 1018 steel and 304 stainless steel bars. The material strengths were unavailable. The connectors in the second series were fabricated from A36 steel bars. The mill certified steel yield strength and ultimate strength are 49.1 ksi and 70.4 ksi. The welds were performed using the SMAW process. The 1018 steel connectors were welded with E7018 electrodes. The stainless steel connectors were welded with 308-16 electrodes. Welding was conducted at room temperature; no preheat was used.

Subassembly Details

The subassembly was developed assuming that the connectors are spaced at 4 feet and embedded in a double tee panel with a 2ft distance from the DT web to the free flange face. The test specimens are fabricated as one 45 in. square panel with connectors on each face (Figure 4). Two panel thicknesses are used 2 in and 4 in. thick. All the specimen with large connectors were fabricated using the Elevation type 1(Figure 4), the specimen with small connectors in the first series were fabricated using the Elevation type 2(Figure 4), and the specimen with small connectors in the second series were fabricated using the Elevation type 3(Figure 4). The panels are reinforced with welded wire reinforcement to meet ACI temperature and shrinkage reinforcement requirements. In addition to the WWR, conventional reinforcement is used to maintain integrity during testing. The bars are placed diagonally across the panel to minimize influence on the connector response.

Panel Fabrication

The panels were fabricated at Lehigh University ATLSS Research Center. Four connectors were used in each panel. The fabrication setups of the two test series are illustrated in Figure 5 and Figure 6. The six connectors of series 1and two connectors of series 2 prior to concrete placement are detailed in Figure 7 .

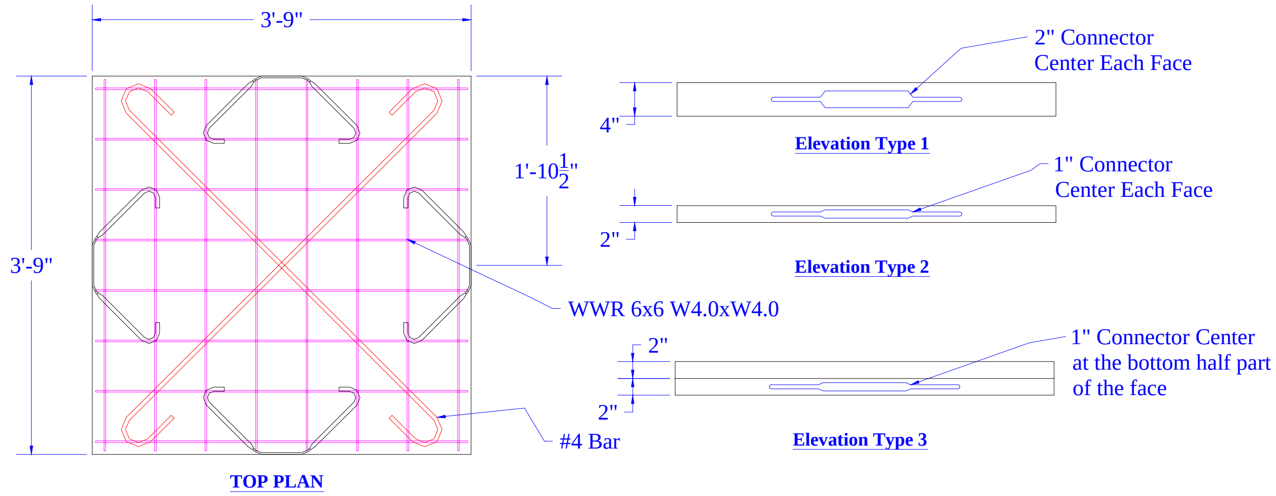


Figure 4: Specimen details

Figure 5: Fabrication setup of test series 1

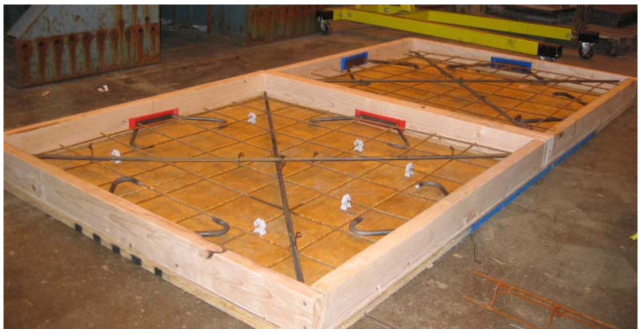


Figure 6: Fabrication setup of test series 2

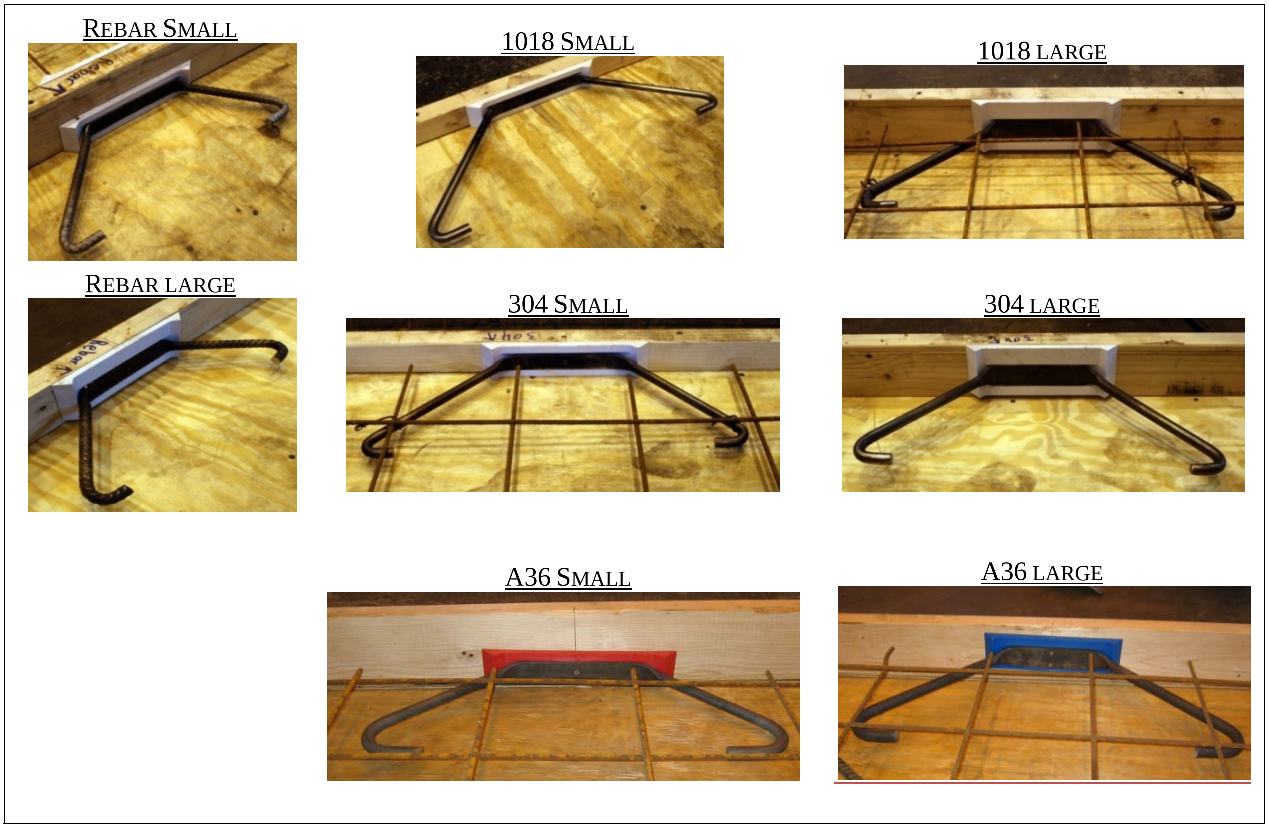


Figure 7: Fabrication details

TESTING CONFIGURATION

The panels were tested in three loading configurations: in-plane shear, in-plane tension, and out-of-plane shear. Simplified setups were used to quickly evaluate the performance. The loading system does not provide significant restraint out of the axis of loading. In conventional diaphragms restraint is provided by the proximity of the connections to other structural members. Since these restraints are not included the strengths measured represent a lower bound on the capacity of the connectors. The setup for each connector is detailed in this section.

Out-of-plane Shear

The out-of-plane shear test was performed to quantify the behavior of the conenctor when the panels are subjected to vertical loads. A self-reacting frame is used as shown in Figure 8. The test frame consists of W6 section and C6 channels. The test slab was sandwiched between the W6 support beams and the tube steel columns. The columns were spaced at 40in. to limit the affect on the connection failure mode. The load was measured with a load cell in-line with the loading jack. Displacement was measured using a linear voltage displacement transducer (LVDT) connected to the connection.

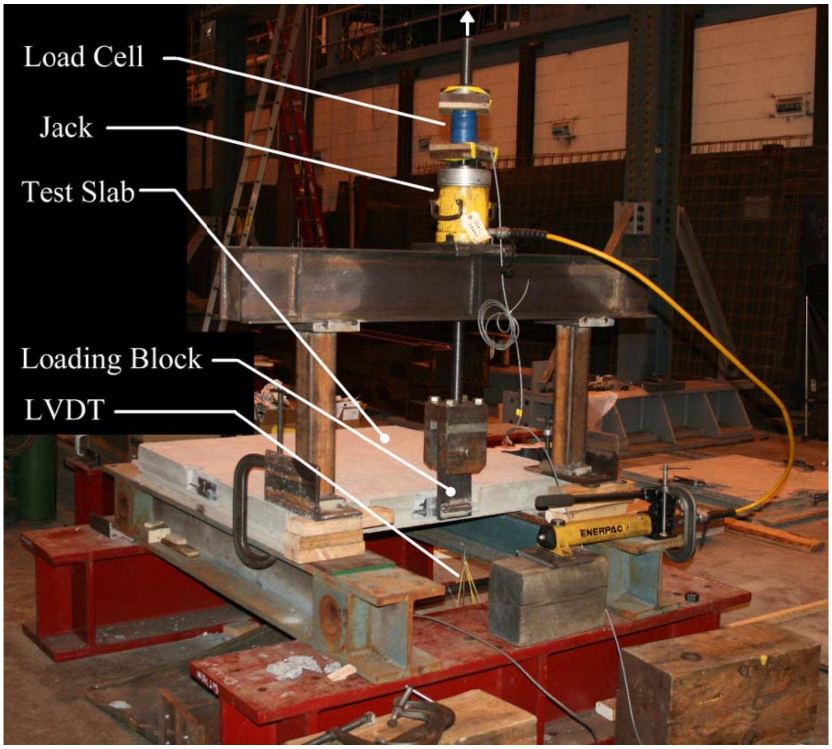


Figure 8: Out-of-plane test setup

In-plane Shear

The in-plane shear test was performed to quantify the behavior of the conenctor when the panels are subjected to longitudinal shear. A self-reacting frame is used as shown in Figure 9. The test frame consists of W6 section and C6 channels. The test slab was sandwiched between the W6 support beams. The fixture was configured so the beams acted in bearing on the side of the panel 24in. away from the connector. This limited the affect of the supports on the connection failure mode. Displacement was measured with a linear voltage displacement transducer attached to the connection. The shear displacements measured represent only one panel. To compare the results with past research conducted on two connected panels the displacements presented in this report must be multiplied by a factor of 2.0. Load was measured with a load cell in-line with the loading jack.

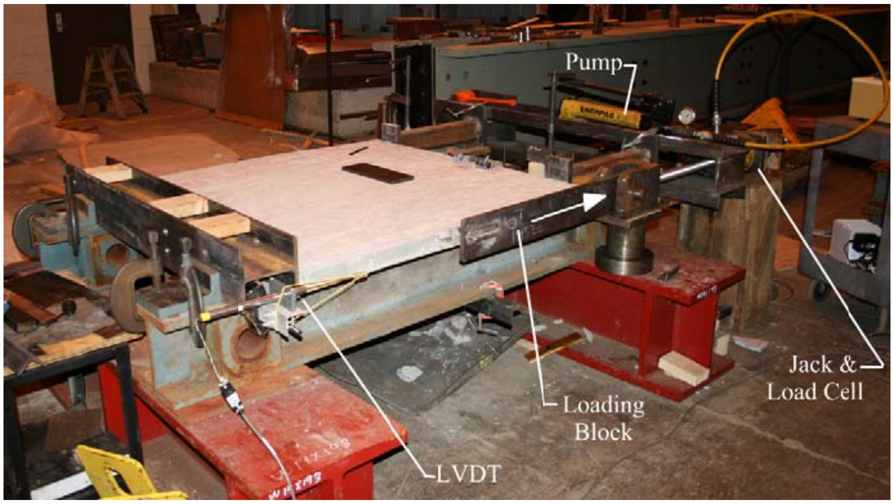


Figure 9: In-plane shear test setup

In-plane Tension

The in-plane tension test was performed to quantify the behavior of the conenctor when the panels are subjected to opening loads such as those that occur during thermal variations or under earthquakes. A self-reacting frame is used as shown in Figure 10. The test frame consists of W6 section and C6 channels. The test slab was loaded between the tube steel columns. The columns were spaced at 40in. to limit the affect on the connection failure mode. Displacement was and load was measured in-line with the applied force demands.

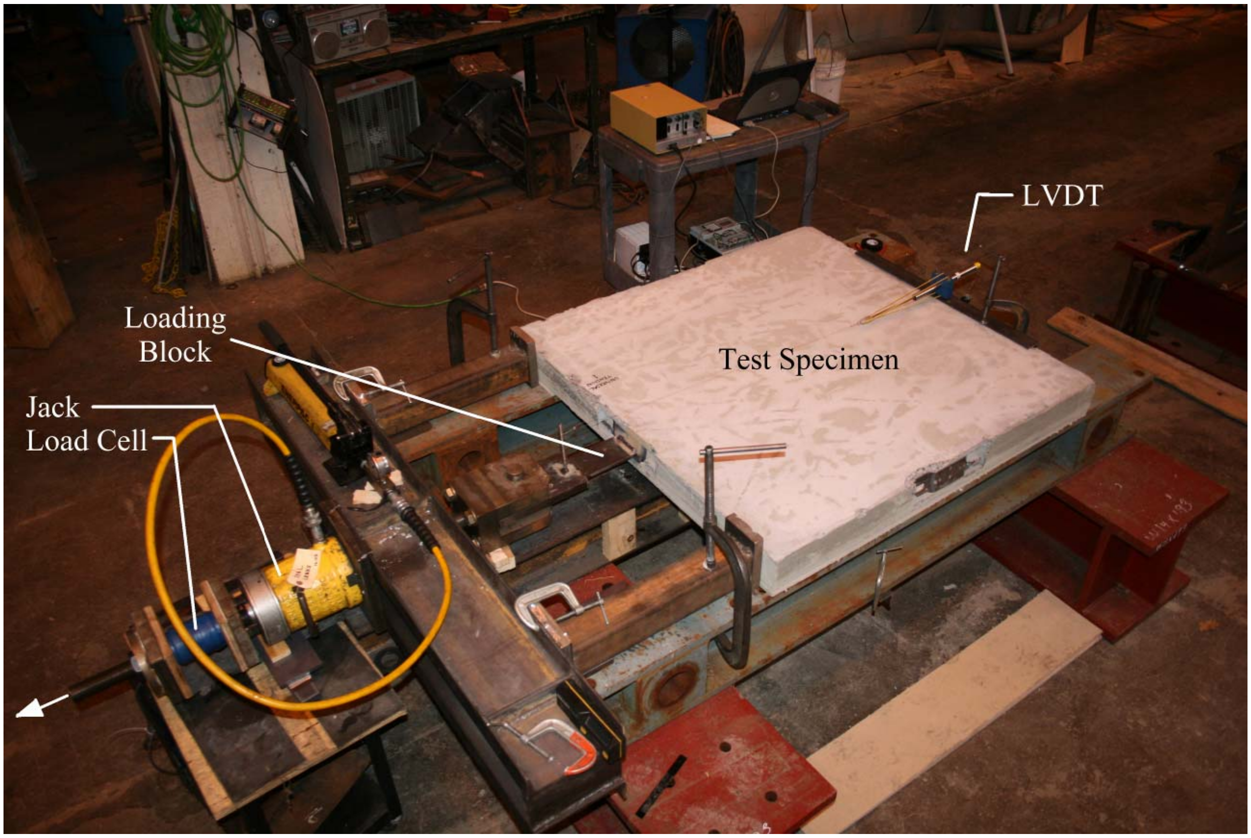


Figure 10: In-plane tension test setup

Loading History

In general all connections were tested in a monotonically increasing displacement. The displacement reported represents the deformation of one connector. In diaphragm connections where two connectors are welded together it can be assumed that the deformation capacity will be doubled.

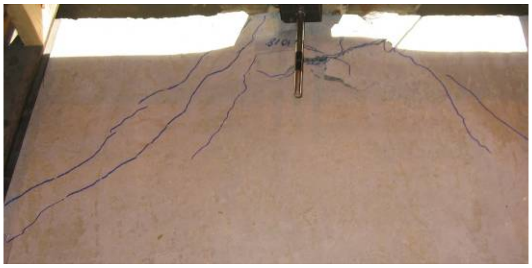
SUMMARY OF TEST SERIES 1

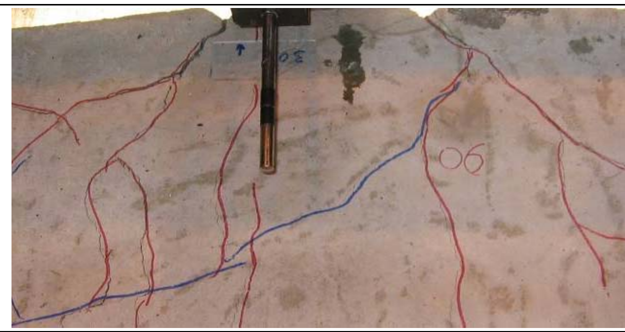
The following table summarizes the results of the experimental tests series 1. The results are presented for each connector type of the first series. The connectors were tested under three loading configurations, namely (1) In-plane Tension, (2) In-plane Shear, and (3) Out-of-plane Shear. For each test configuration, the peak load, corresponding deformation, and max design load are presented. The max design load represents the largest load that the connector can reliably resist. No factors of safety have been applied to this value. The max design value represents the average of the two tests when the higher value does not exceed the lower value by more than 5 percent and the lower value when the test results vary by more than 5%. For tests with less than two repetitions the max load value is used.

Table 2: Summary Results of Test Series 1

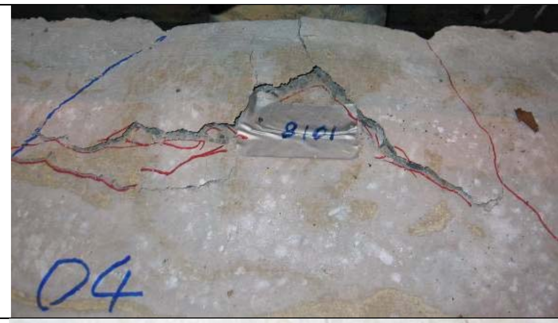
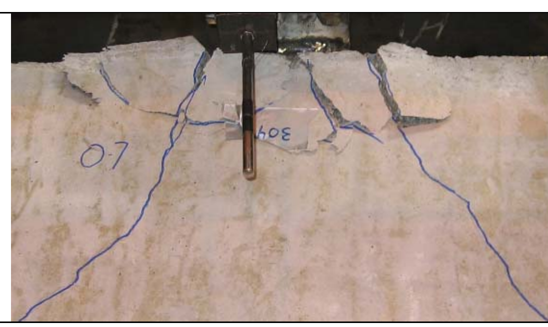
Description	ID	Loading Protocol	Maximum Load [kips]	Corresponding Deformation [in.]	Max Design Load [kips]
1018 Steel 1.0 x 1/2	A1	Out-of-Plane Shear	2.64	0.25	2.64
	A2	Out-of-Plane Shear	3.49	1.13	
	A3	In-Plane Tension	5.38	0.37	5.38
	A4	In-Plane Shear	15.85	0.38	15.85
	A5	In-Plane Shear	17.53	0.28	
304 Stainless 1.0 x 1/2	B1	Out-of-Plane Shear	3.37	0.96	3.02
	B2	Out-of-Plane Shear	3.02	1.52	
	B3	In-Plane Tension	5.95	0.35	5.95
	B4	In-Plane Shear	13.87	0.23	13.87
	B5	In-Plane Shear	16.47	0.30	
304 Rebar 1.0 x 1/2	C1	In-Plane Tension	9.34	0.33	9.34
	C2	In-Plane Shear	18.96	0.17	18.96
1018 Steel 1.5 x 5/8	D1	Out-of-Plane Shear	6.87	0.36	6.39
	D2	Out-of-Plane Shear	6.39	0.25	
	D3	In-Plane Tension	8.99	0.45	8.99
	D4	In-Plane Shear	29.23	0.30	29.9
	D5	In-Plane Shear	30.63	0.26	
304 Stainless 1.5 x 5/8	E1	Out-of-Plane Shear	6.45	0.20	6.39
	E2	Out-of-Plane Shear	6.33	0.30	
	E3	In-Plane Tension	14.36	0.59	14.36
	E4	In-Plane Shear	29.00	0.64	28.5
	E5	In-Plane Shear	27.92	0.55	
304 Rebar 1.5 x 5/8	F1	In-Plane Tension	12.59	0.37	12.59
	F2	In-Plane Shear	32.67	0.21	32.67

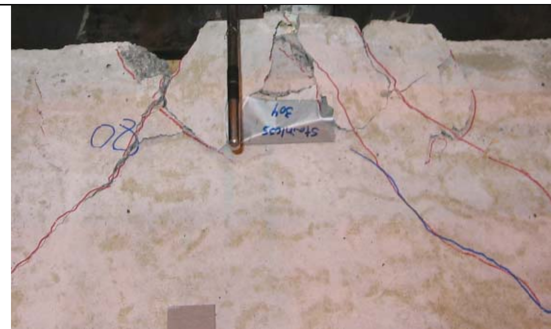
The failure modes of each experiment are summarized in Table 3. The Out-of plane shear tests were controlled by concrete breakout. Consequently, the connectors embedded in the 2-in. thick panels provided lower out-of-plane shear resistance than those embedded in 4-in. thick panels. In-plane shear and tension failure modes were controlled by concrete crushing at the connector legs and fracture of the slug-to-connector weld.

Table 3: Failure Modes of Test Series 1			
Specimen	ID	Loading Protocol	Failure Modes
1018 Steel 1.0 x 1/2	A1	Out-of-Plane Shear	
1018 Steel 1.0 x 1/2	A2	Out-of-Plane Shear	
1018 Steel 1.0 x 1/2	A3	In-Plane Tension	
1018 Steel 1.0 x 1/2	A4	In-Plane Shear	
1018 Steel 1.0 x 1/2	A5	In-Plane Shear	

304 Stainless 1.0 x 1/2	B1	Out-of-Plane Shear	
304 Stainless 1.0 x 1/2	B2	Out-of-Plane Shear	
304 Stainless 1.0 x 1/2	B3	In-Plane Tension	
304 Stainless 1.0 x 1/2	B4	In-Plane Shear	
304 Stainless 1.0 x 1/2	B5	In-Plane Shear	

304 Rebar 1.0 x 1/2	C1	In-Plane Tension	
304 Rebar 1.0 x 1/2	C2	In-Plane Shear	
304 Rebar 1.5 x 5/8	F1	In-Plane Tension	
304 Rebar 1.5 x 5/8	F2	In-Plane Shear	
1018 Steel 1.5 x 5/8	D1	Out-of-Plane Shear	

1018 Steel 1.5 x 5/8	D2	Out-of-Plane Shear	
1018 Steel 1.5 x 5/8	D3	In-Plane Tension	
1018 Steel 1.5 x 5/8	D4	In-Plane Shear	
1018 Steel 1.5 x 5/8	D5	In-Plane Shear	
304 Stainless 1.5 x 5/8	E1	Out-of-Plane Shear	

304 Stainless 1.5 x 5/8	E2	Out-of-Plane Shear	
304 Stainless 1.5 x 5/8	E3	In-Plane Tension	
304 Stainless 1.5 x 5/8	E4	In-Plane Shear	
304 Stainless 1.5 x 5/8	E5	In-Plane Shear	

Out-of-Plane Shear Response

The measured load and displacement of the connectors subject to out-of-plane shear is summarized in Figure 11. D2 and A1 failed at lower displacements due to earlier crack formation on the top face of the panel. Specimen B2 had a lower elastic range than B1 due to a pre-existing crack on the top face of the panel. All connectors had a measured out-of-plane capacity greater than 2500 lbs. The strength of the connectors embedded in 2 in. panels was close to the 2500 lb strength while the connectors embedded in 4 in. panels had an approximate strength of 5500 lbs. The failure mode of these connections was a result of concrete breakout above the connector. The use of a topping slab above the connectors used in the 2in. thick panels would significantly enhance the out-of-plane capacity.

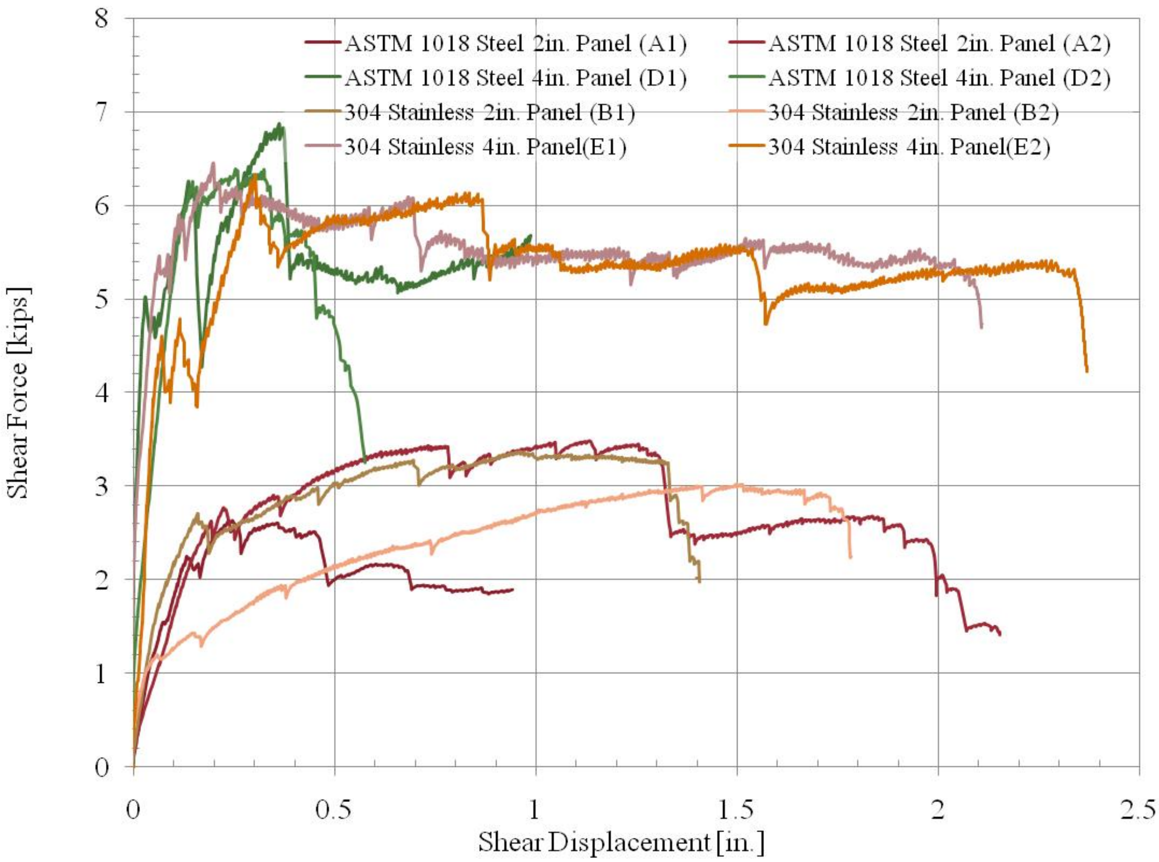


Figure 11: Out-of-plane shear response

In-Plane Shear Response

The measured load and displacement of the connectors subject to in-plane shear is summarized in Figure 12 and Figure 13. All connectors aside from the rebar connection details were evaluated through two experiments. The connections that were evaluated twice exhibited a consistent response between the tests. In general the connections exhibited yielding of the faceplate followed by concrete crushing. The ultimate failure modes in many cases were controlled by fracture of the faceplate adjacent to the weld.

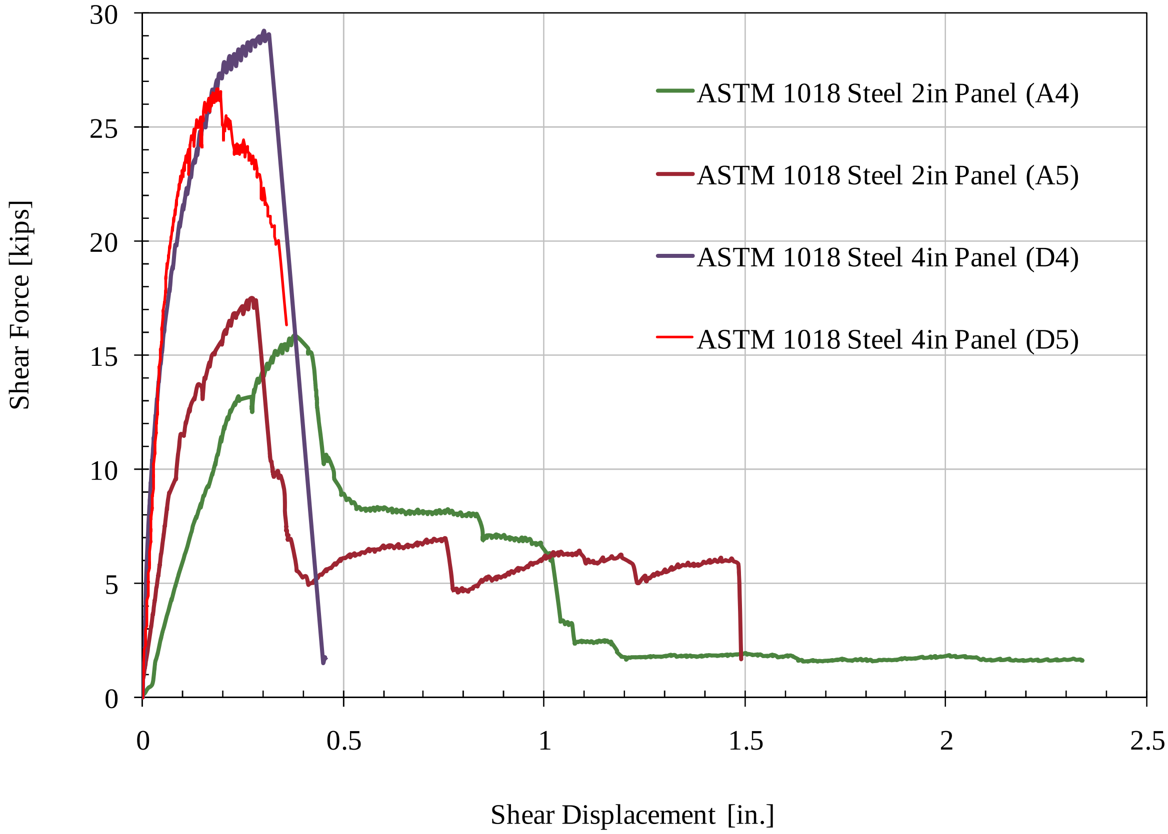


Figure 12: In-plane shear response 1018 Steel specimens

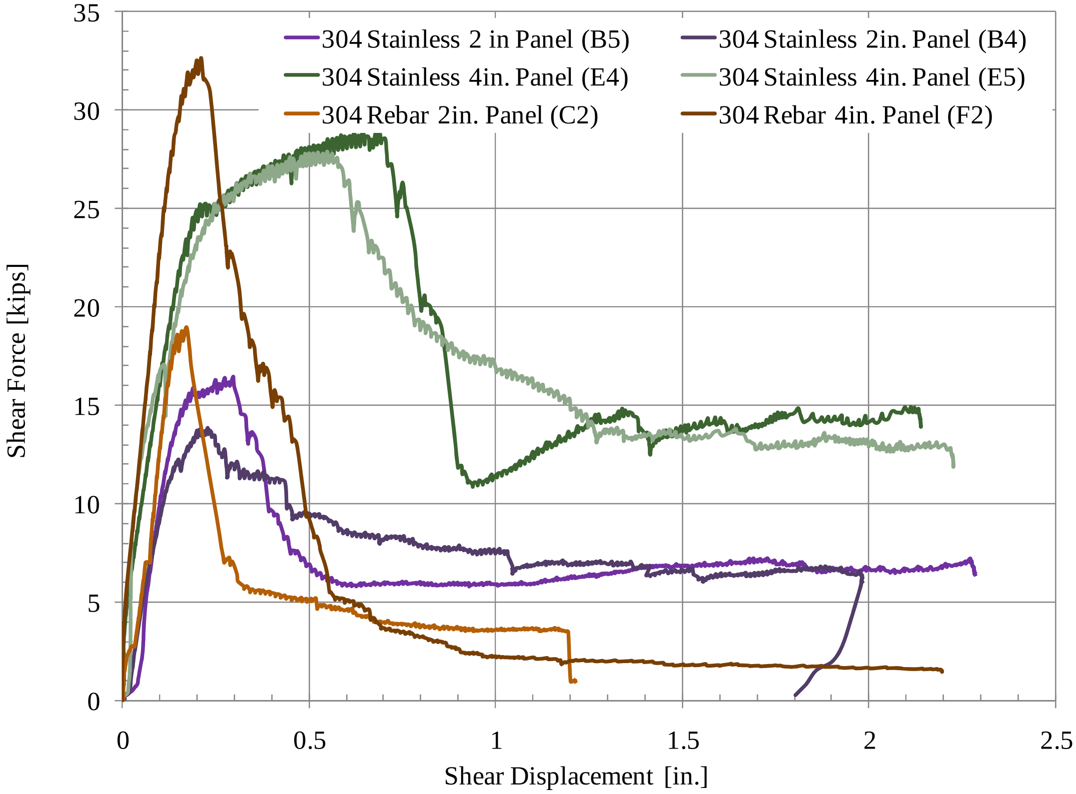


Figure 13: In-plane shear response 304 stainless steel specimens

In-Plane Tension Response

The measured load and displacement of the connectors subject to in-plane tension is summarized in Figure 14. The strength of the connectors varied from approximately 5 to 14 kips. All connectors reached their peak resistance prior to an opening of 0.6 in.

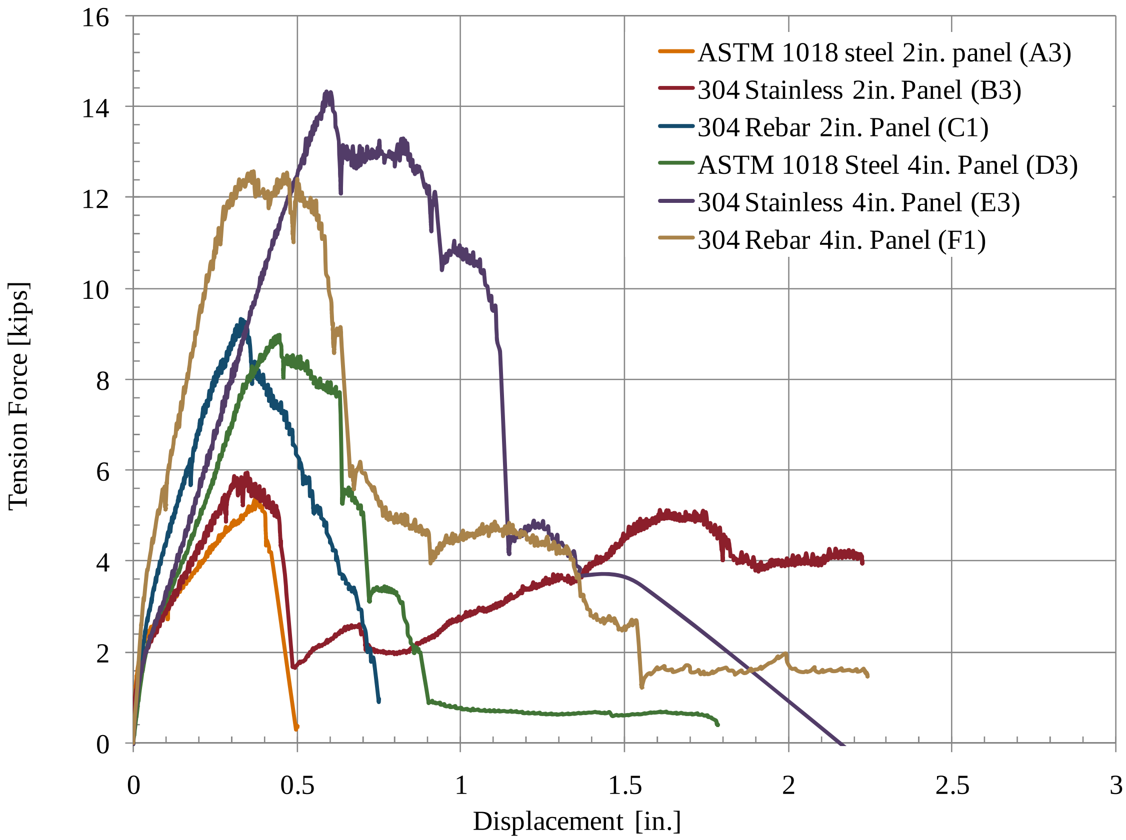


Figure 14: In-plane tension response

SUMMARY OF TEST SERIES 2

The results of the experimental tests series 2 are summarized in Table 4. The results are presented for each connector type of the second series. The connectors were tested under two loading configurations, namely (1) In-plane Tension, (2) In-plane Shear. For each test configuration, the peak load, corresponding deformation, and max design load are presented. The max design load represents the largest load that the connector can reliably resist. No factors of safety have been applied to this value. The max design value represents the average of the two tests when the higher value does not exceed the lower value by more than 5 percent and the lower value when the test results vary by more than 5%. For tests with less than two repetitions the max load value is used.

Table 4: Summary Results of Test Series 2

Description	ID	Loading Protocol	Maximum Load [kips]	Corresponding Deformation [in.]	Max Design Load [kips]
A36 Steel 1.0 x 1/2	G1	In-Plane Shear	16.21	0.39	16.52
	G2	In-Plane Shear	16.82	0.32	
	G3	In-Plane Tension	7.60	0.59	7.21
	G4	In-Plane Tension	7.21	0.63	
A36 Steel 1.5 x 5/8	H1	In-Plane Shear	27.93	0.43	27.68
	H2	In-Plane Shear	27.42	0.46	
	H3	In-Plane Tension	11.74	0.57	11.74
	H4	In-Plane Tension	12.59	0.77	

The failure modes of each experiment in the second test series are summarized in Table 5. In-plane shear and tension failure modes were controlled by fracture of connector faceplate.

Table 5: Failure Modes of Test Series 2

Specimen	ID	Loading Protocol	Failure Modes
A36 Steel 1.0 x 1/2	G1	In-Plane Shear	
A36 Steel 1.0 x 1/2	G2	In-Plane Shear	

A36 Steel 1.0 x 1/2	G3	In-Plane Tension	
A36 Steel 1.0 x 1/2	G4	In-Plane Tension	
A36 Steel 1.5 x 5/8	H1	In-Plane Shear	
A36 Steel 1.5 x 5/8	H2	In-Plane Shear	

A36 Steel 1.5 x 5/8	H3	In-Plane Tension	
A36 Steel 1.5 x 5/8	H4	In-Plane Tension	

In-Plane Shear Response

The measured load and displacement of the connectors subject to in-plane shear is summarized in Figure 15. Both large and small A36 connectors were evaluated through two experiments. The connections that were evaluated twice exhibited a consistent response between the tests. In general the connections failed due to abrupt faceplate fracture.

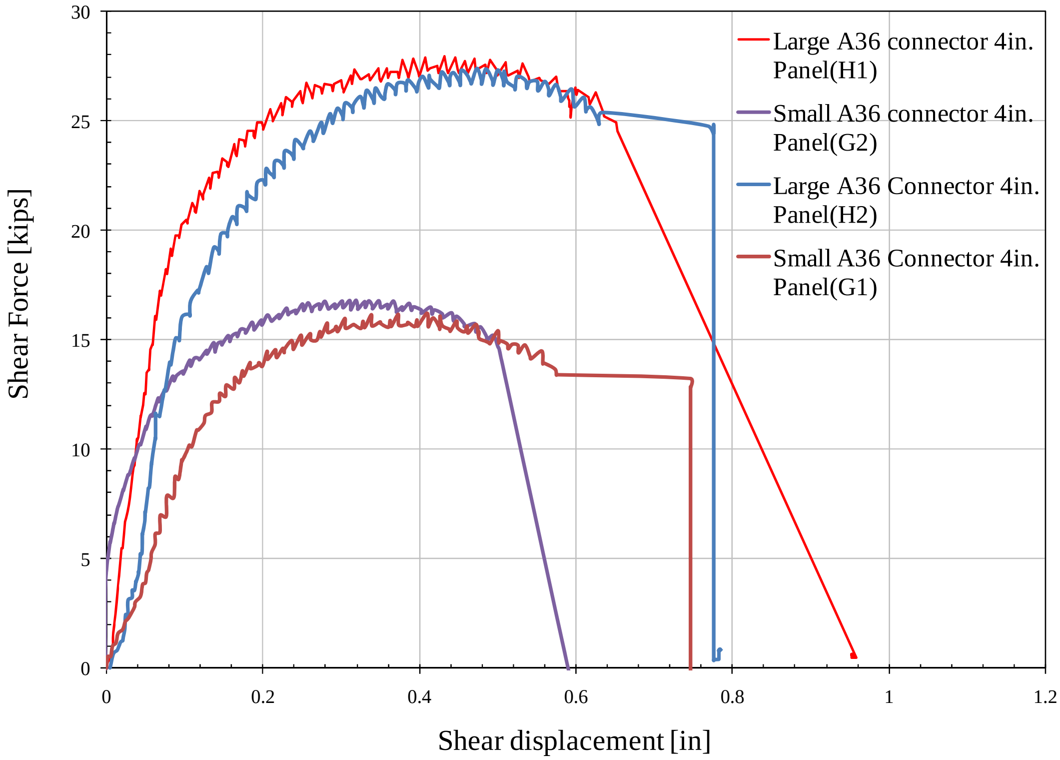


Figure 15: In-plane shear response A36 Steel specimens

In-Plane Tension Response

The measured load and displacement of the connectors subject to in-plane tension is summarized in Figure 16. Both large and small A36 connectors were evaluated through two experiments. The connections that were evaluated twice exhibited a consistent response between the tests. In general the connections exhibited yielding and bending of the faceplate. The ultimate failure modes were controlled by fracture of the faceplate adjacent to the weld. All connectors reached their peak resistance prior to an opening of 0.8 in.

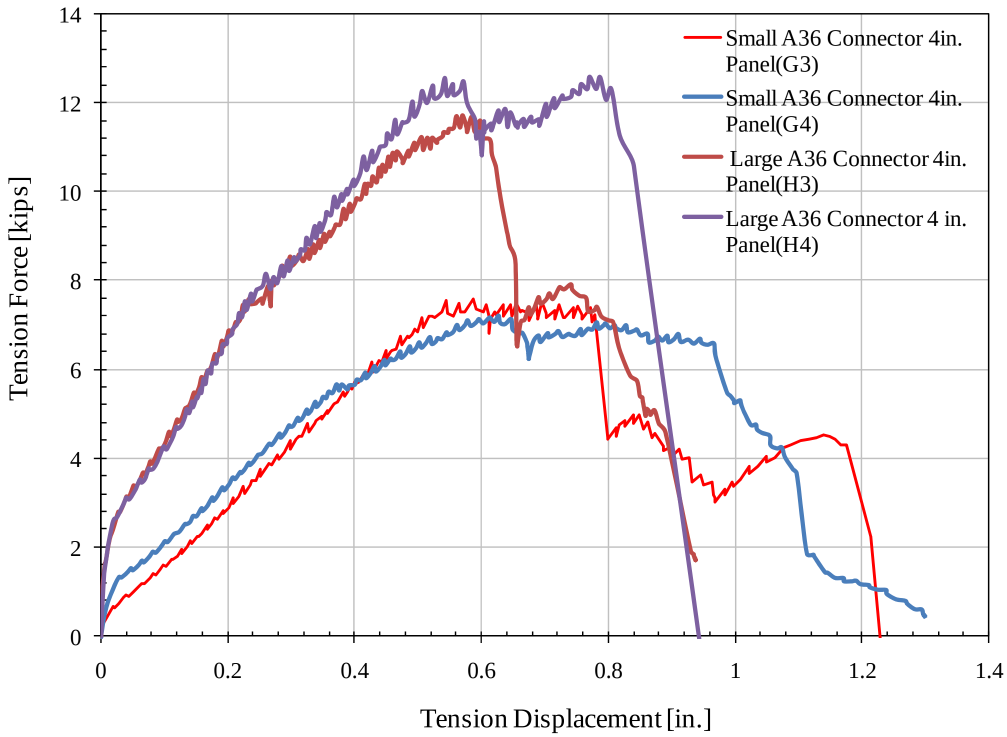
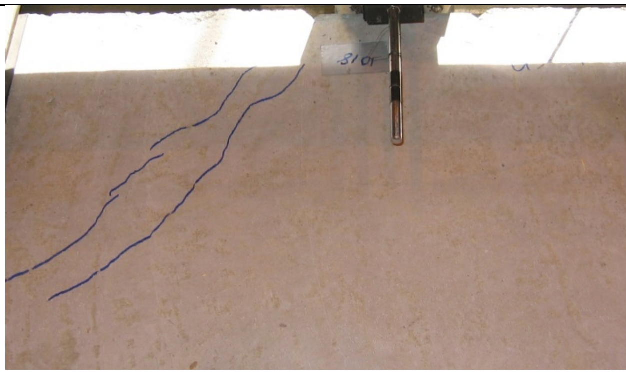
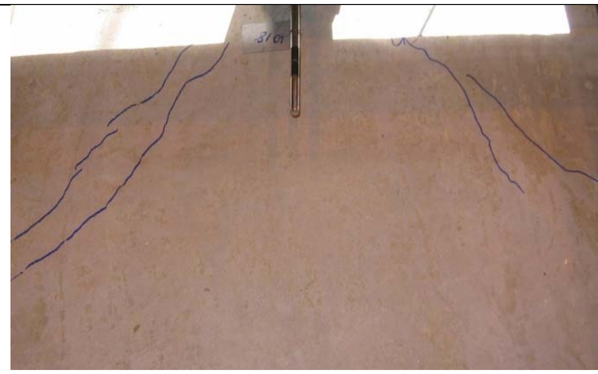


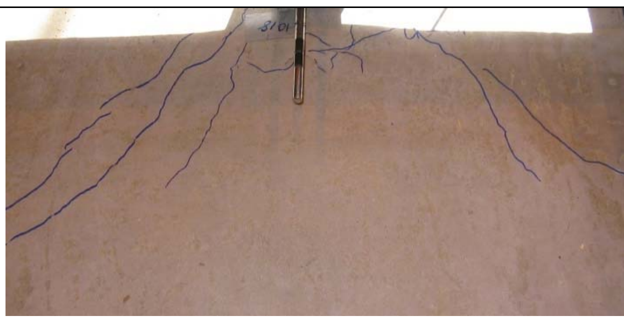
Figure 16: In-plane tension response

TEST A1: 1018 CONNECTION UNDER MONOTONIC OUT-OF-PLANE SHEAR (2-IN PANEL)

The performance of the Universal connection subject to monotonic, out-of-plane shear is presented in this section. The connector was subjected to shear displacement in the vertical direction with the in plane shear and tension displacements restrained. The performance of the panel was characterized by cracking and spalling in the area where the connector legs are embedded. Failure occurred when the connector legs had been pulled free of the surrounding concrete. The observed key events and the corresponding displacement level are presented in Table 6. The photos of the damage are presented in Figure 17 and Figure 18. The global force deformation response and backbone curve are presented in Table 7 and Figure 19.


a) 0.16-in.


b) 0.25-in.


c) 0.45-in.

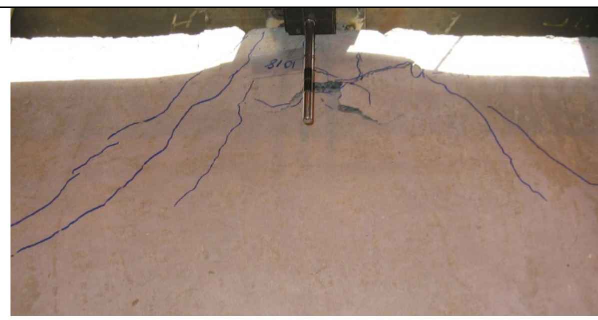

d) 0.68-in

Figure 17: Damage state at various out-of-plane shear deformations A1

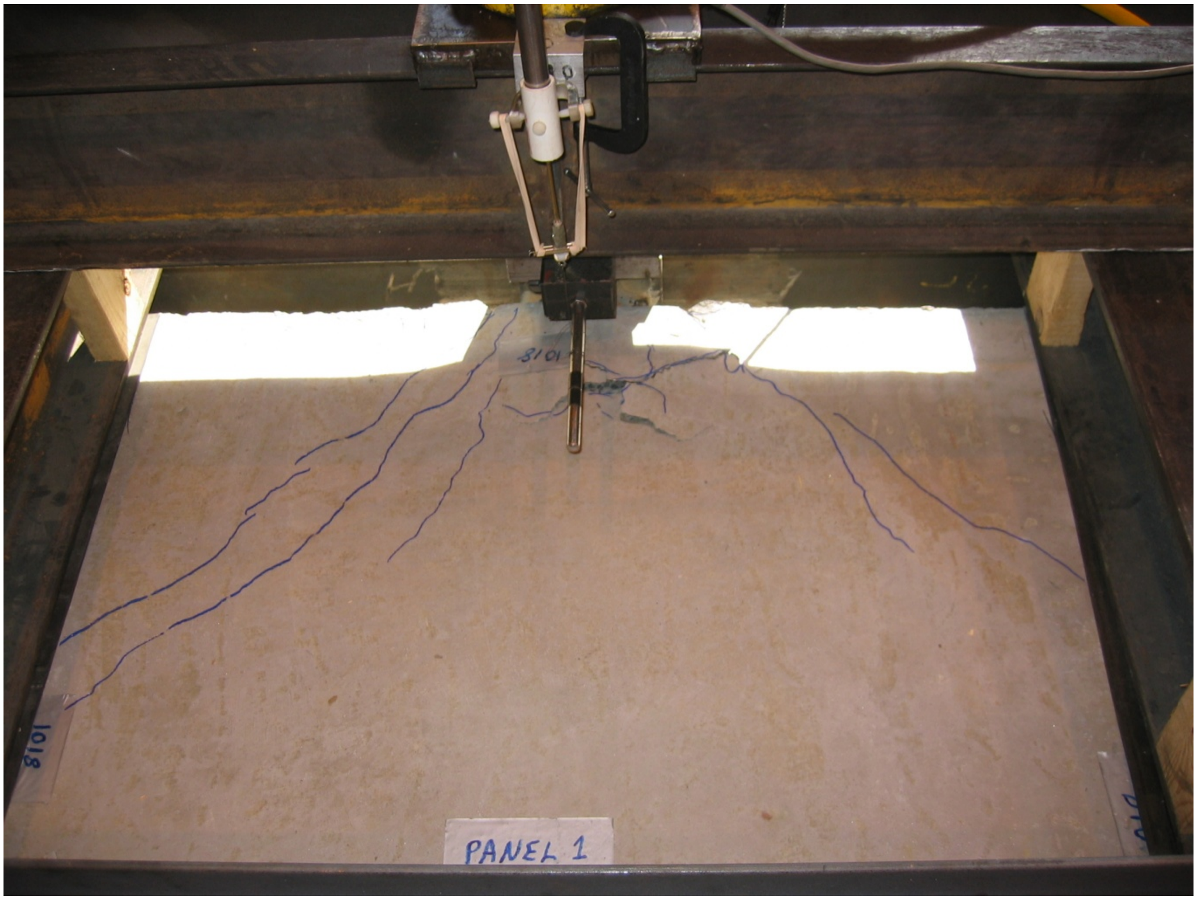


Figure 18: Damage at end of test A1

Table 6: Key Test Observations (Out-of-plane shear) A1		
Event #	Shear Δ Step [in.]	Event Description
1	0.16	First two diagonal cracks formed on the left side of panel
2	0.25	Two more diagonal cracks formed on the right side of panel
3	0.45	Concrete started spalling and more cracks formed on the panel
4	0.68	Concrete severely spalled
5	0.94	Connector sheared out of panel

Table 7: Experimental Results Backbone Curve (Out-of-plane shear) A1		
Event	Shear Displacement [in.]	Shear Force [kips]
Peak Load	0.25	2.64
End of test	0.93	1.89

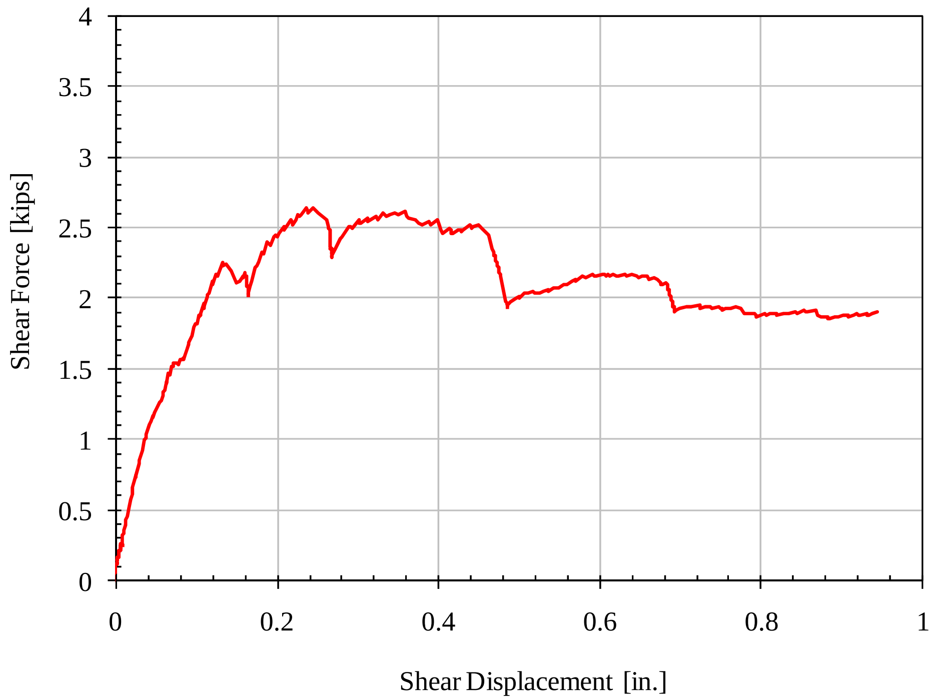
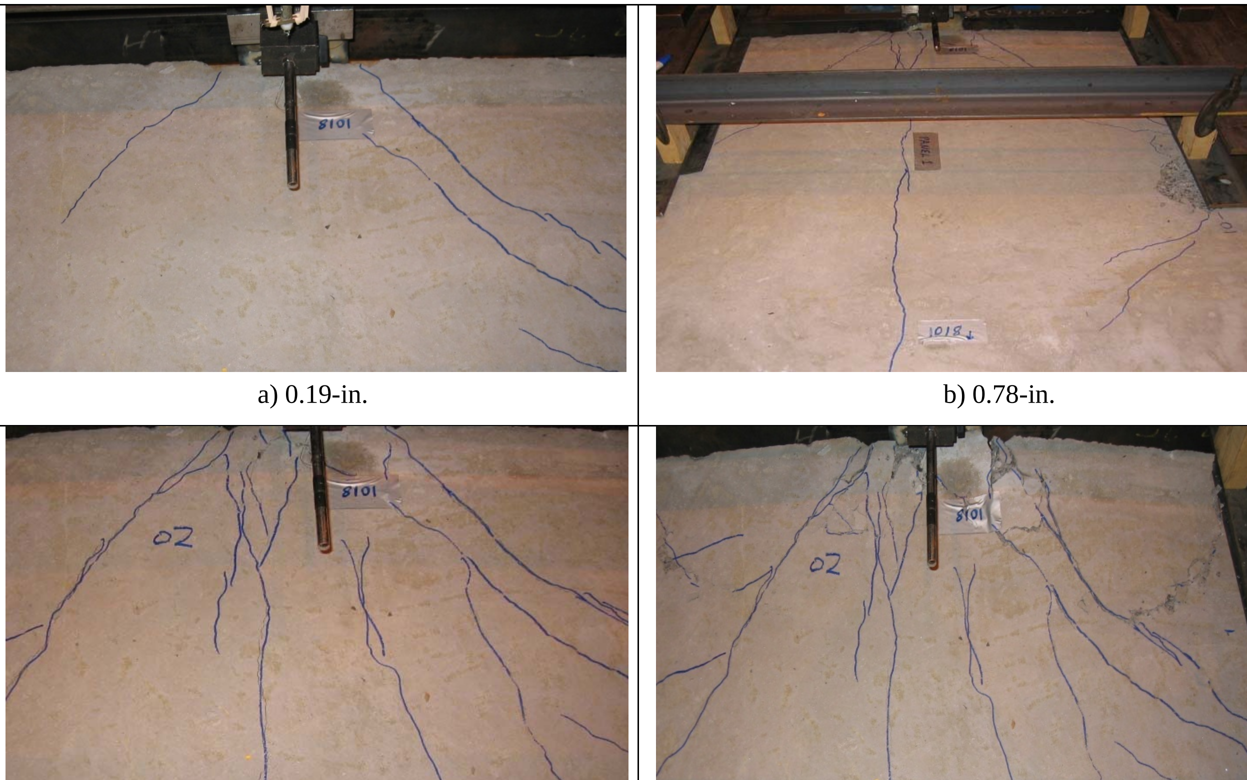


Figure 19: Shear force and displacement (Out-of-plane shear)

TEST A2: 1018 CONNECTION UNDER MONOTONIC OUT-OF-PLANE SHEAR (2-IN PANEL)

The performance of the Universal connection subject to monotonic, out-of-plane shear is presented in this section. The connector was subjected to shear displacement in the vertical direction with the in plane shear and tension displacements restrained. The performance of the panel was characterized by cracking and spalling in the area where the connector legs are embedded. Failure occurred when the connector legs had been pulled free of the surrounding concrete. The observed key events and the corresponding displacement level are presented in Table 8. The photos of the damage states are presented in Figure 20. The initial and final conditions of the specimen are presented in Figure 21 and Figure 22. The global force deformation response and backbone curve are presented in Table 9 and Figure 23.



a) 0.19-in. b) 0.78-in.

c) 1.13-in. d) 2.15-in

Figure 20: Damage state at various out-of-plane shear deformations A2

Figure 21: Damage at beginning of test A2

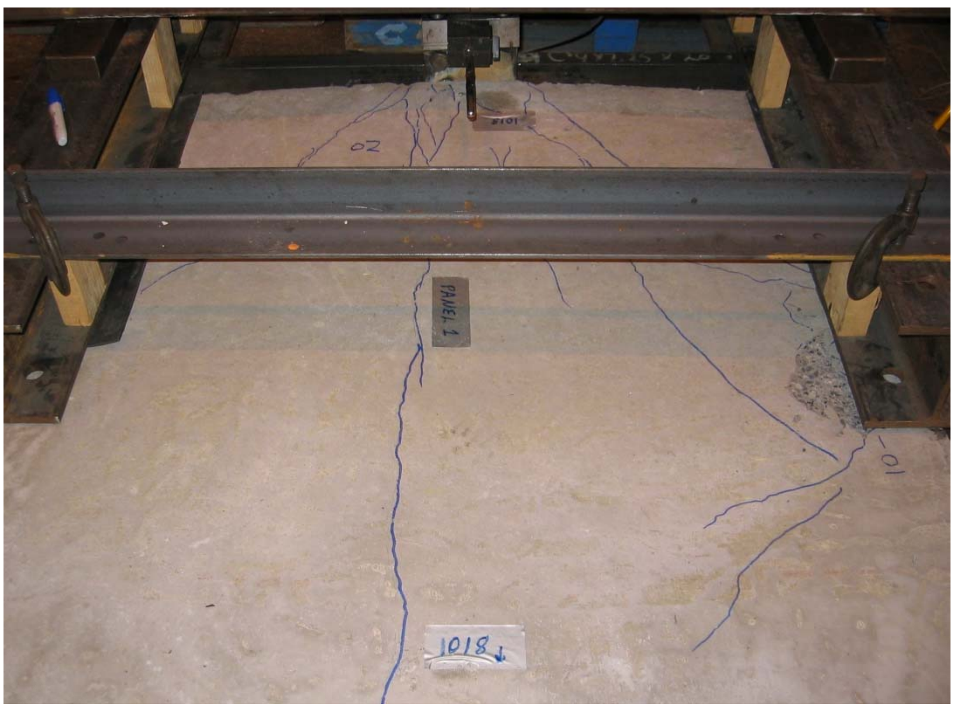


Figure 22: Damage at end of test A2

Table 8: Key Test Observations (Out-of-plane shear) A2		
Event #	Shear Δ Step [in.]	Event Description
1	0.19	First diagonal crack formed on the panel
2	0.25	Existing crack progressed
3	0.37	One transverse crack formed on the panel
4	0.78	The transverse crack extended through the whole panel
5	1.05	More cracks formed, and existing cracks extended

Table 8: Key Test Observations (Out-of-plane shear) A2		
Event #	Shear Δ Step [in.]	Event Description
6	1.13	Concrete started spalling
4	1.30	Cracks around the connector formed
5	2.15	Connector sheared out of panel

Table 9: Experimental Results Backbone Curve (Out-of-plane shear) A2		
Event	Shear Displacement [in.]	Shear Force [kips]
Peak Load	1.13	3.48
End of test	2.15	1.42

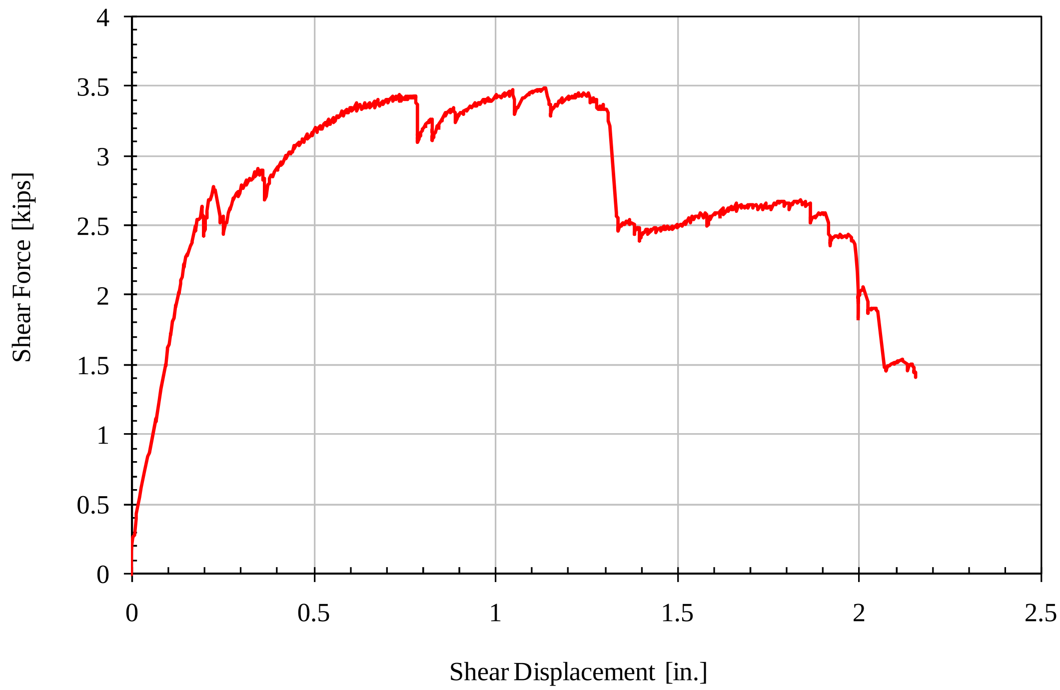


Figure 23: Shear force and displacement (Out-of-plane shear) A2

TEST D1: 1018 CONNECTION UNDER MONOTONIC OUT-OF-PLANE SHEAR (4-IN PANEL)

The performance of the Universal connection subject to monotonic, out-of-plane shear is presented in this section. The connector was subjected to shear displacement in the vertical direction with the in plane shear and tension displacements restrained. The performance of the panel was characterized by cracking and spalling in the area where the connector legs are embedded. Failure occurred when the connector legs had been pulled free of the surrounding concrete. The observed key events and the corresponding displacement level are presented in Table 10. The photos of the damage states are presented in Figure 24. The initial and final conditions of the specimen are presented in Figure 25 and Figure 26. The global force deformation response and backbone curve are presented in Table 11 and Figure 27.

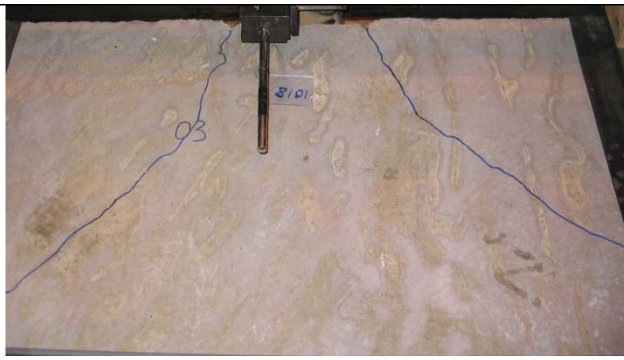
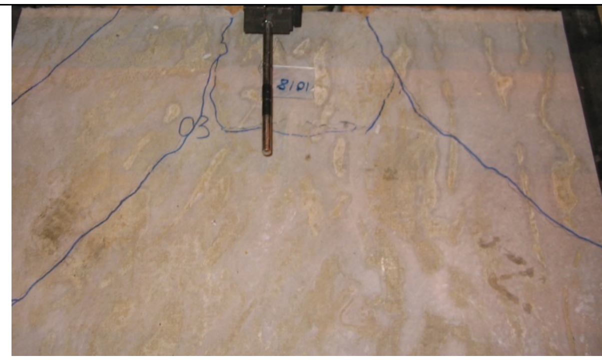
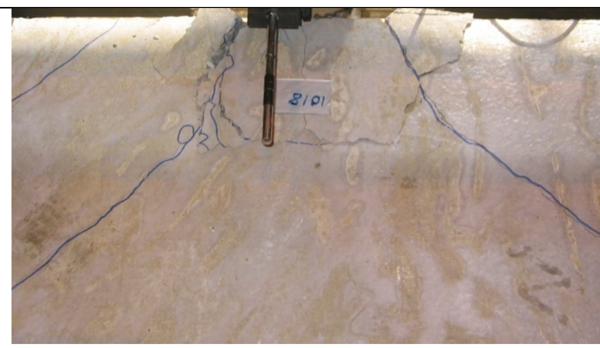
 a) 0.15-in.	 b) 0.38-in.
 c) 0.84-in.	 d) 1.43-in

Figure 24: Damage state at various out-of-plane shear deformations D1

Figure 25: Initial condition of test D1

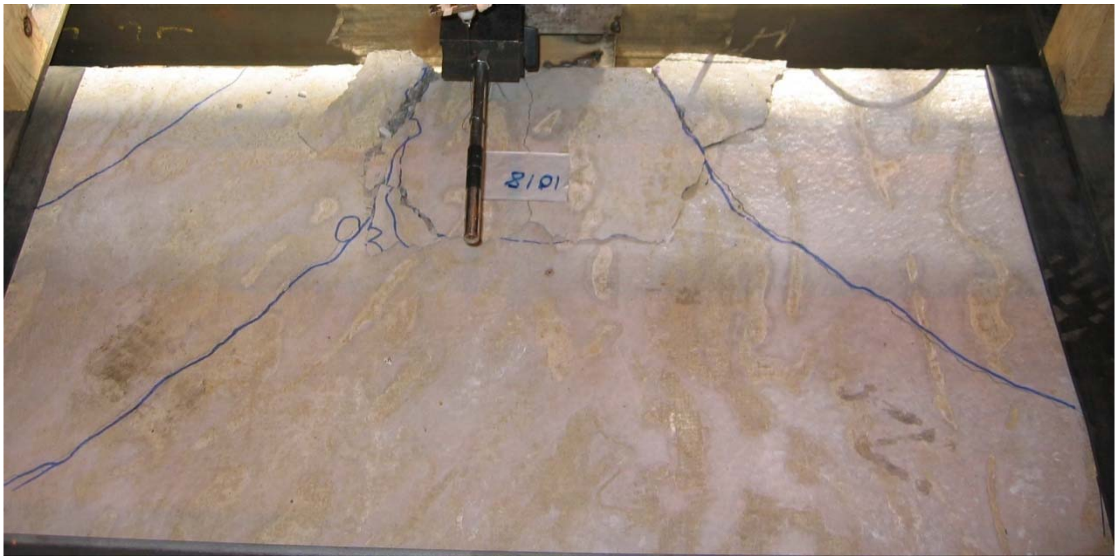


Figure 26: Final condition of test D1

Table 10: Key Test Observations (Out-of-plane shear) D1		
Event #	Shear Δ Step [in.]	Event Description
1	0.15	First two diagonal cracks formed on the panel
2	0.38	One more diagonal cracks formed on the right side of panel; Concrete started spalling
3	0.84	Concrete severely spalled
4	1.43	Connector sheared out of panel

Table 11: Experimental Results Backbone Curve (Out-of-plane shear) D1		
Event	Shear Displacement [in.]	Shear Force [kips]
Peak Load	0.36	6.87
End of test	1.00	5.61

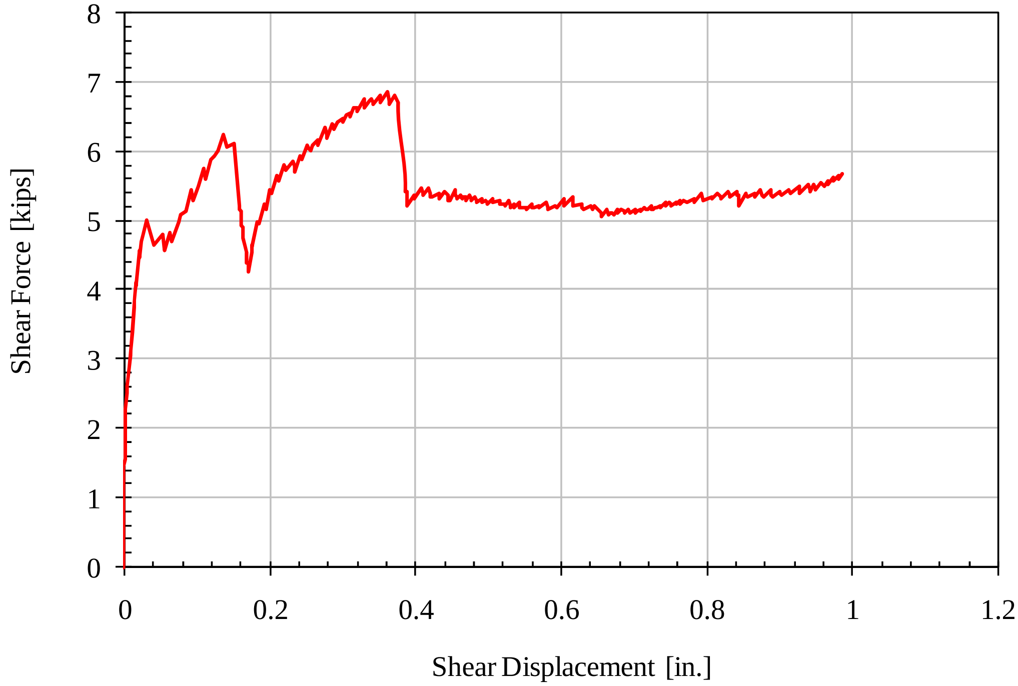
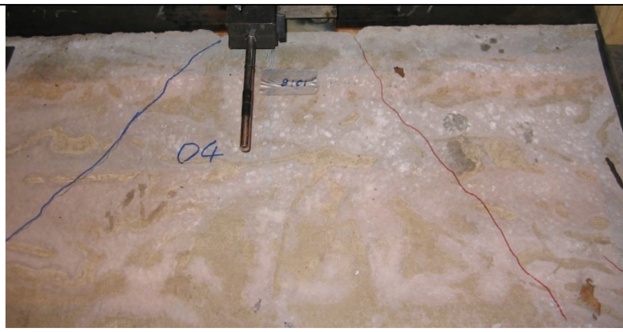


Figure 27: Shear force and displacement (Out-of-plane shear) D1

TEST D2: 1018 CONNECTION UNDER MONOTONIC OUT-OF-PLANE SHEAR (4-IN PANEL)

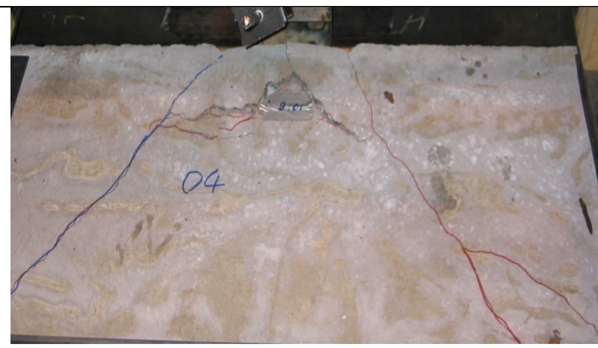
The performance of the Universal connection subject to monotonic, out-of-plane shear is presented in this section. The connector was subjected to shear displacement in the vertical direction with the in plane shear and tension displacements restrained. The performance of the panel was characterized by cracking and spalling in the area where the connector legs are embedded. The connection failed due to the fracture of welding between the slug and loading plate. The observed key events and the corresponding displacement level are presented in Table 12. The photos of the damage states are presented in Figure 28. The initial and final conditions of the specimen are presented in Figure 29 and Figure 30. The global force deformation response and backbone curve are presented in Table 13 and Figure 31.



a) 0.16-in.

b) 0.26-in.

c) 0.45-in.



d) 0.58-in

Figure 28: Damage state at various out-of-plane shear deformations D2

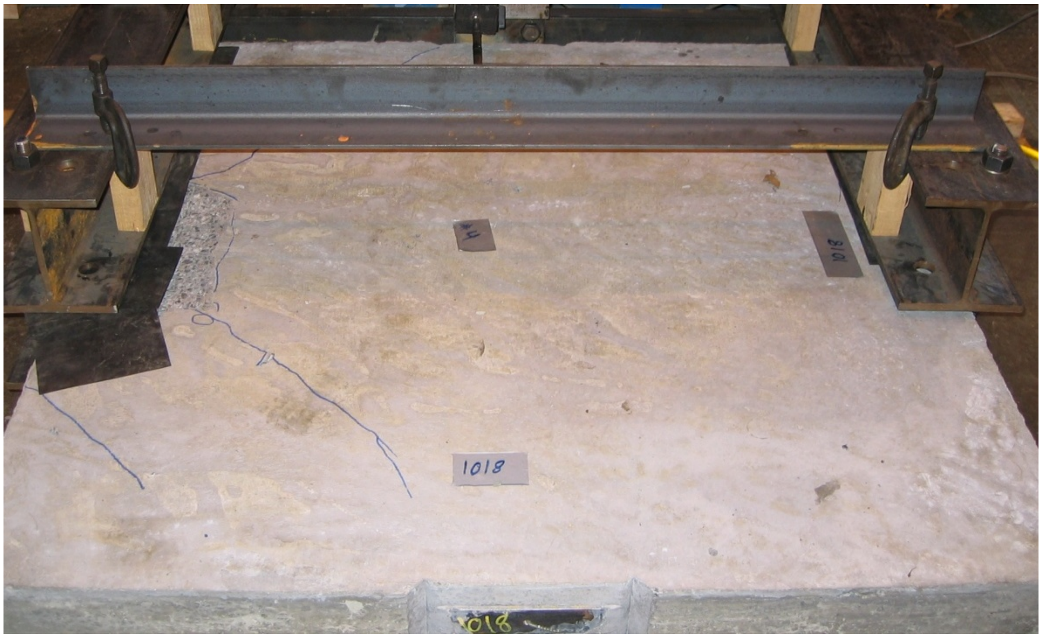


Figure 29: Initial condition of test D2

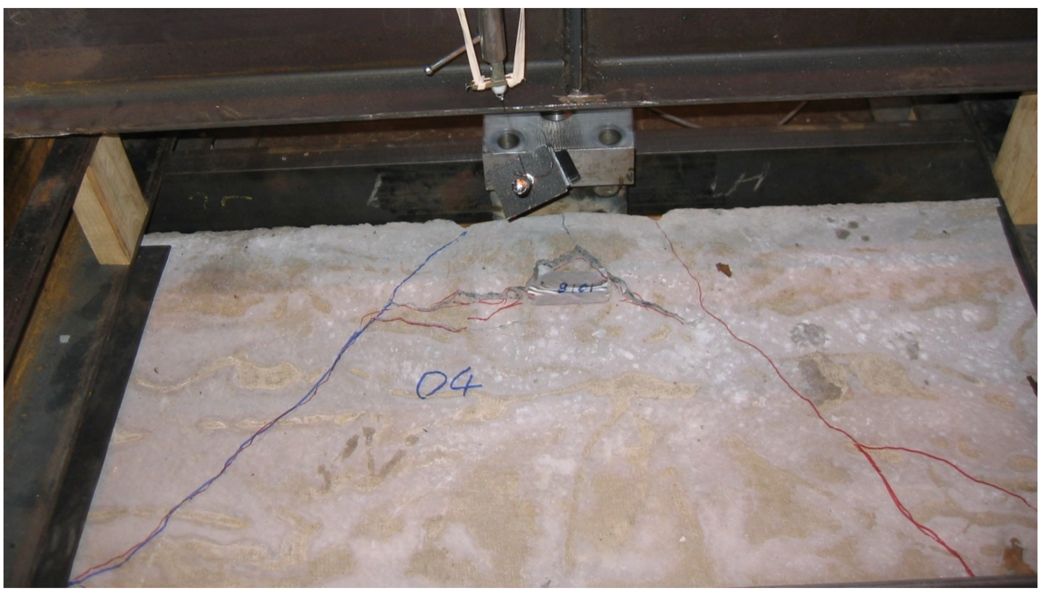


Figure 30: Final condition of test D2

Table 12: Key Test Observations (Out-of-plane shear) D2		
Event #	Shear Δ Step [in.]	Event Description
1	0.16	First diagonal cracks formed on the right side of panel
2	0.26	One more diagonal cracks formed on the right side of panel; Concrete started spalling
3	0.45	Existing cracks progressed; More cracks formed around the connector
4	0.58	Fracture of welding between the connector slug and back plate

Table 13: Experimental Results Backbone Curve (Out-of-plane shear) D2		
Event	Shear Displacement [in.]	Shear Force [kips]
Peak Load	0.25	6.39
End of test	0.58	3

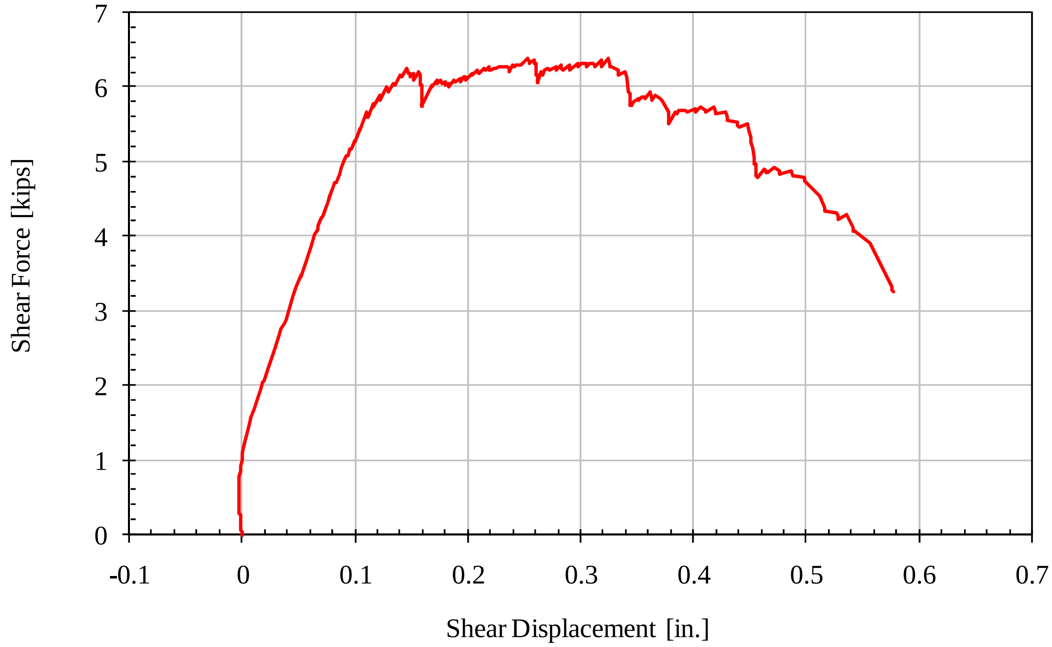
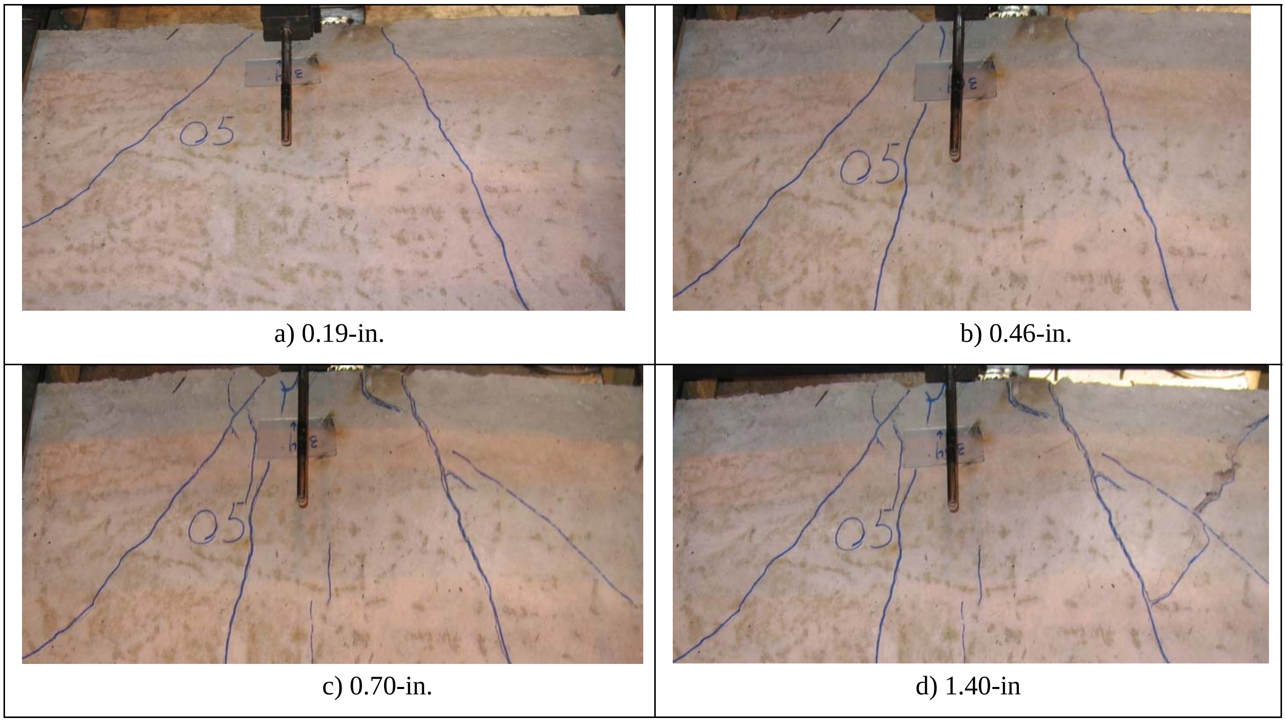


Figure 31: Shear force and displacement (Out-of-plane shear) D2

TEST B1: STAINLESS CONNECTION UNDER MONOTONIC OUT-OF-PLANE SHEAR (2-IN PANEL)

The performance of the Universal connection subject to monotonic, out-of-plane shear is presented in this section. The connector was subjected to shear displacement in the vertical direction with the in plane shear and tension displacements restrained. The performance of the panel was characterized by cracking and spalling in the area where the connector legs are embedded. Failure occurred when the connector legs had been pulled free of the surrounding concrete. The observed key events and the corresponding displacement level are presented in Table 14. The photos of the damage states are presented in Figure 32. The initial and final conditions of the specimen are presented in Figure 33 and Figure 34. The global force deformation response and backbone curve are presented in Table 15 and Figure 35.



a) 0.19-in.   b) 0.46-in.

c) 0.70-in.   d) 1.40-in

Figure 32: Damage state at various out-of-plane shear deformations B1

Figure 33: Initial condition of test B1

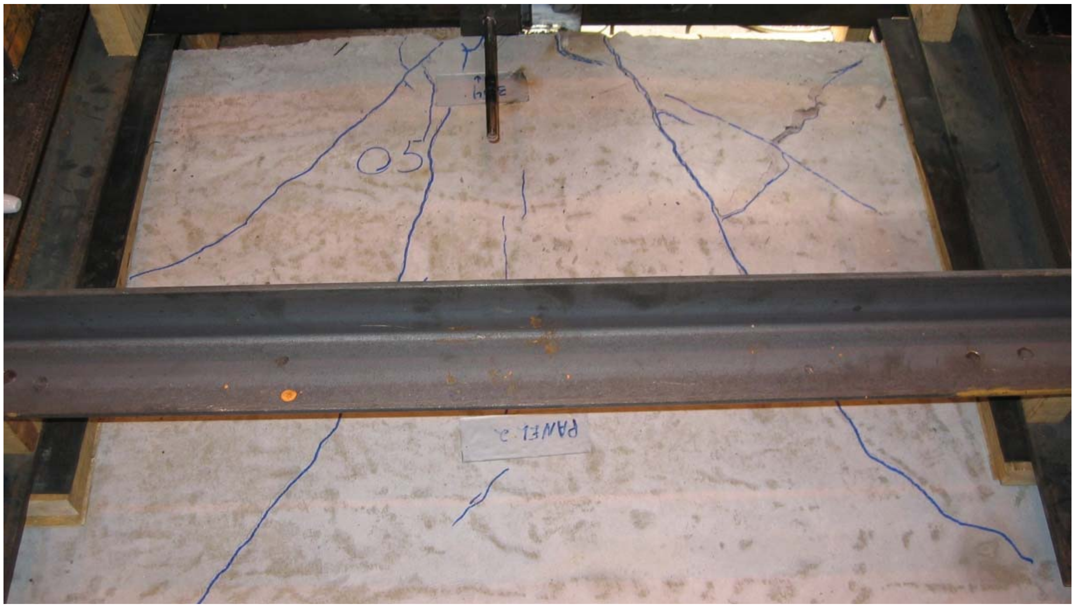


Figure 34: Final condition of test B1

Table 14: Key Test Observations (Out-of-plane shear) B1		
Event #	Shear Δ Step [in.]	Event Description
1	0.19	First two diagonal cracks formed on the panel
2	0.46	One more diagonal crack formed on the left side of panel; Existing cracks extended.
3	0.70	Existing cracks progressed; More cracks formed around the connector; Concrete started spalling.
4	1.40	Connector sheared out of panel

Table 15: Experimental Results Backbone Curve (Out-of-plane shear) B1		
Event	Shear Displacement [in.]	Shear Force [kips]
Peak Load	0.96	3.37
End of test	1.40	1.98

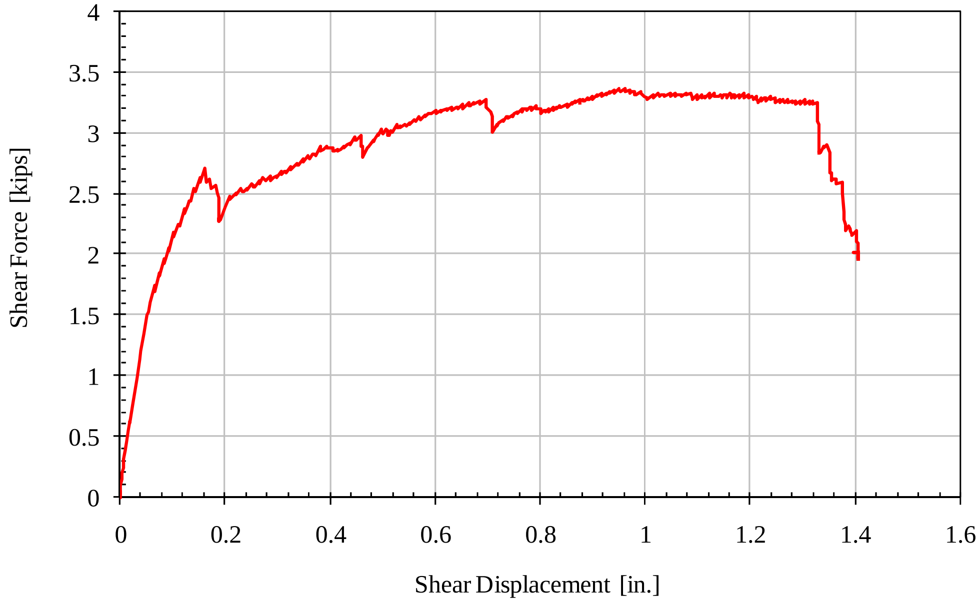
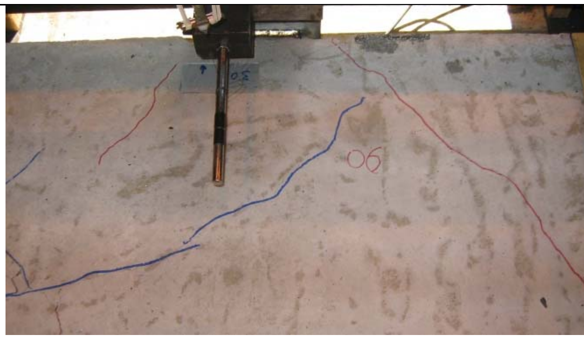


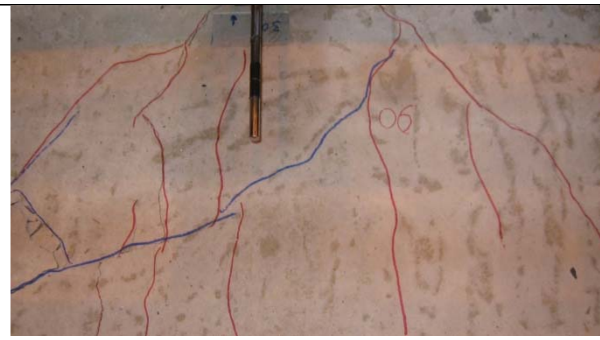
Figure 35: Shear force and displacement (Out-of-plane shear) B1

TEST B2: STAINLESS CONNECTION UNDER MONOTONIC OUT-OF-PLANE SHEAR (2-IN PANEL)

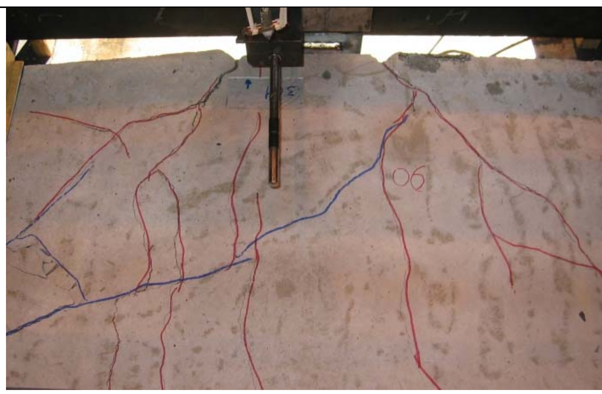
The performance of the Universal connection subject to monotonic, out-of-plane shear is presented in this section. The connector was subjected to shear displacement in the vertical direction with the in plane shear and tension displacements restrained. The performance of the panel was characterized by cracking and spalling in the area where the connector legs are embedded. And finally the test was ended due to the failure of concrete panel in this area. The observed key events and the corresponding displacement level are presented in Table 16. The photos of the damage states are presented in Figure 36. The initial and final conditions of the specimen are presented in Figure 37 and Figure 38. The global force deformation response and backbone curve are presented in Table 17 and Figure 39.



a) 0.15-in.



b) 0.74-in.



c) 1.67-in.

d) 1.78-in

Figure 36: Damage state at various out-of-plane shear deformations B2

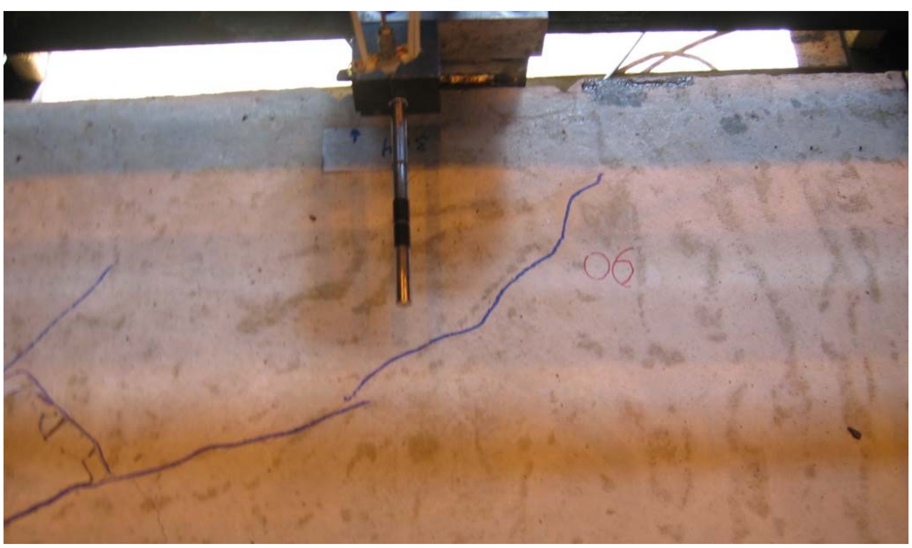


Figure 37: Initial condition of test B2

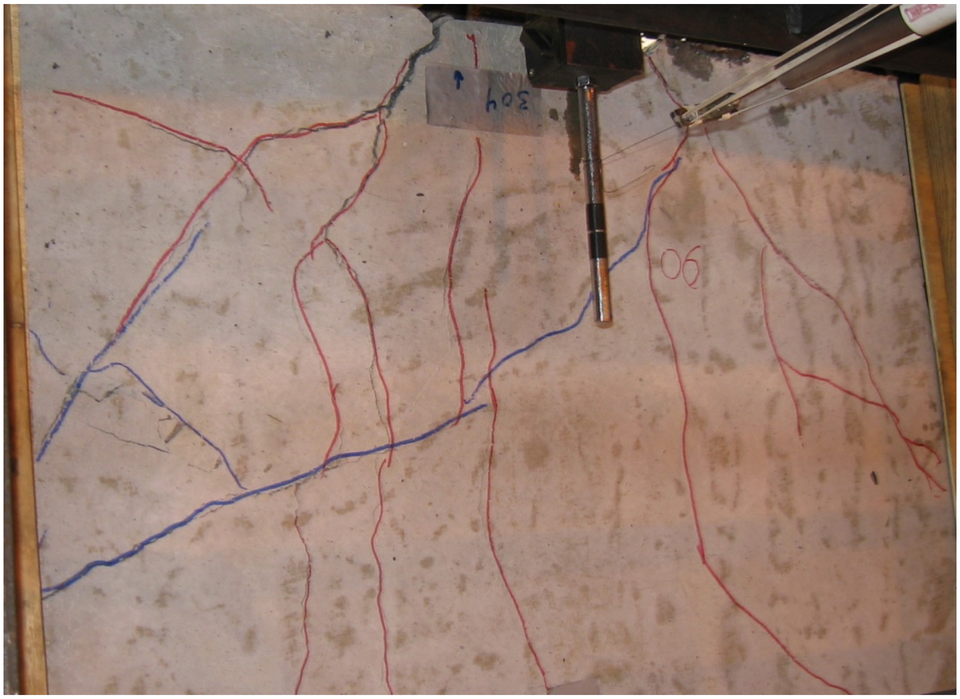


Figure 38: Final condition of test B2

Table 16: Key Test Observations (Out-of-plane shear) B2		
Event #	Shear Δ Step [in.]	Event Description
1	0.19	First two diagonal cracks formed on the panel
2	0.74	More cracks formed on the panel; Existing cracks extended.
3	1.67	Existing cracks progressed; More cracks formed around the connector
4	1.78	Concrete panel failed in the area where the connector leg embedded

Table 17: Experimental Results Backbone Curve (Out-of-plane shear) B2		
Event	Shear Displacement [in.]	Shear Force [kips]
Peak Load	1.52	3.02
End of test	1.78	2.33

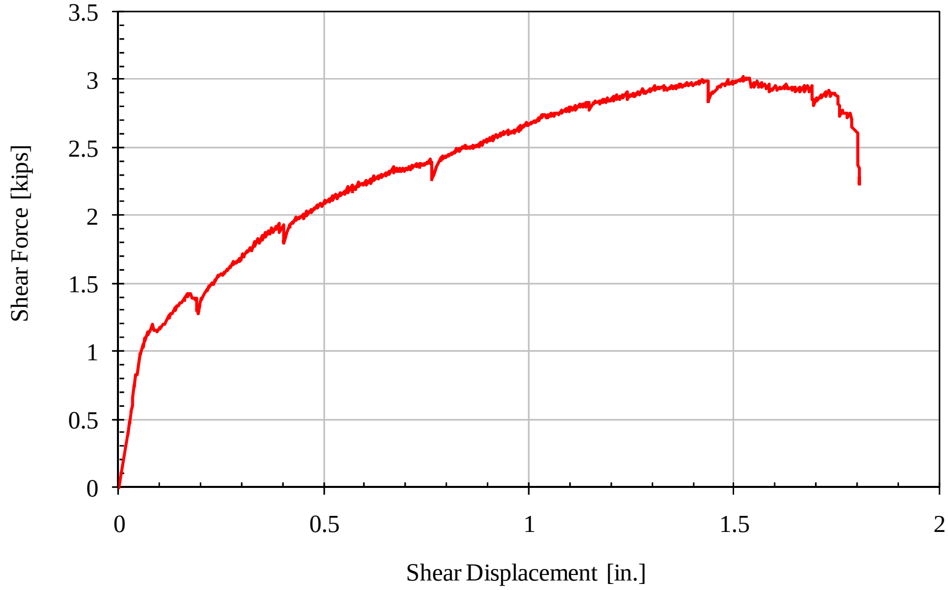
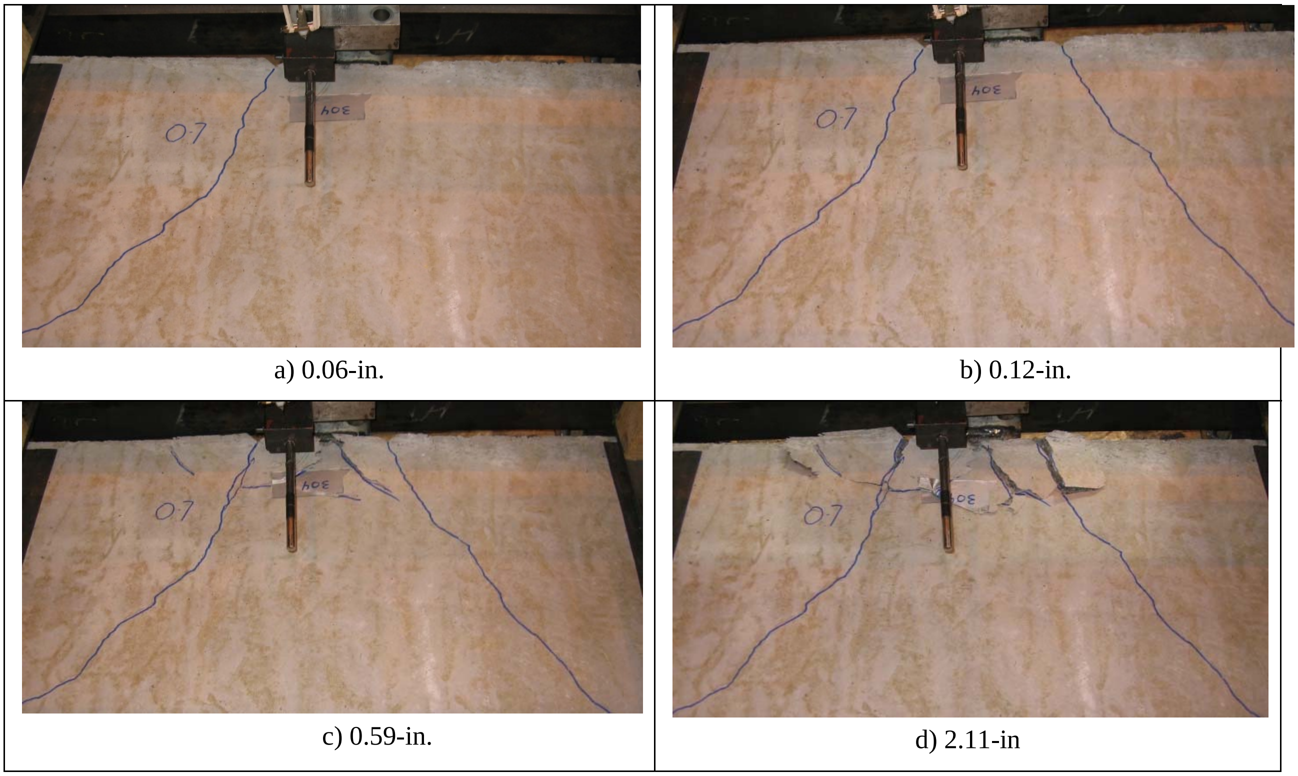


Figure 39: Shear force and displacement (Out-of-plane shear) B2

TEST E1: STAINLESS CONNECTION UNDER MONOTONIC OUT-OF-PLANE SHEAR (4-IN PANEL)

The performance of the Universal connection subject to monotonic, out-of-plane shear is presented in this section. The connector was subjected to shear displacement in the vertical direction with the in plane shear and tension displacements restrained. The performance of the panel was characterized by cracking and spalling in the area where the connector legs are embedded. The test was conducted until the load cell was out of stroke. The observed key events and the corresponding displacement level are presented in Table 18. The photos of the damage states are presented in Figure 40. The initial and final conditions of the specimen are presented in Figure 41 and Figure 42. The global force deformation response and backbone curve are presented in Table 19 and Figure 43.



a) 0.06-in. b) 0.12-in.

c) 0.59-in. d) 2.11-in

Figure 40: Damage state at various out-of-plane shear deformations E1

Figure 41: Initial condition of test E1

Figure 42: Final condition of test E1

Table 18: Key Test Observations (Out-of-plane shear) E1		
Event #	Shear Δ Step [in.]	Event Description
1	0.06	First diagonal crack formed on left side of the panel
2	0.12	One more diagonal crack formed on right side of the panel
3	0.59	More small cracks formed around the connector, concrete started spalling
4	1.23	Concrete continually spalled
5	2.11	The load cell was out of stroke

Table 19: Experimental Results Backbone Curve (Out-of-plane shear) E1		
Event	Shear Displacement [in.]	Shear Force [kips]
Peak Load	0.20	6.45
End of test	2.11	4.70

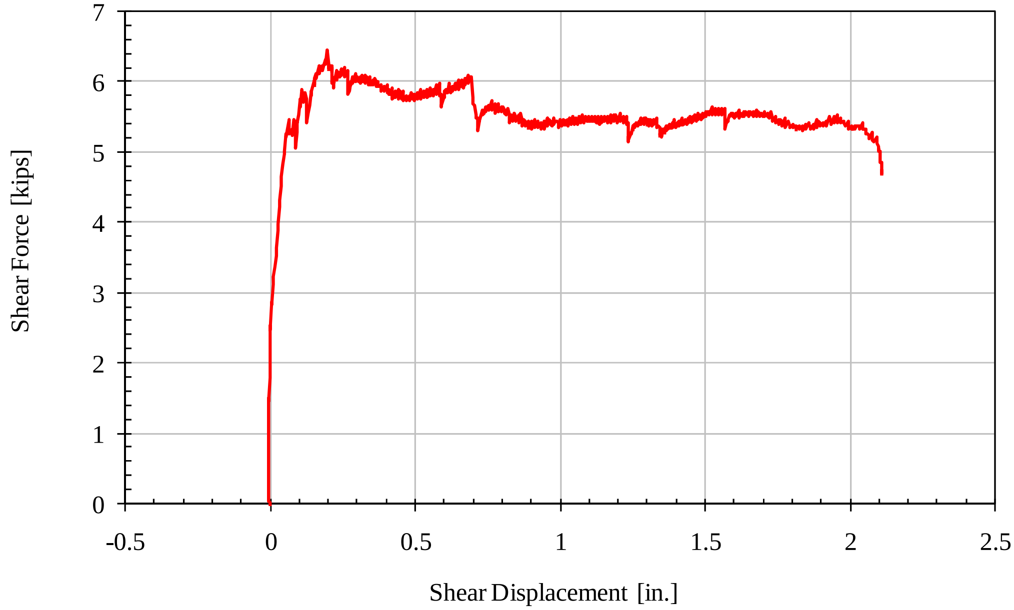
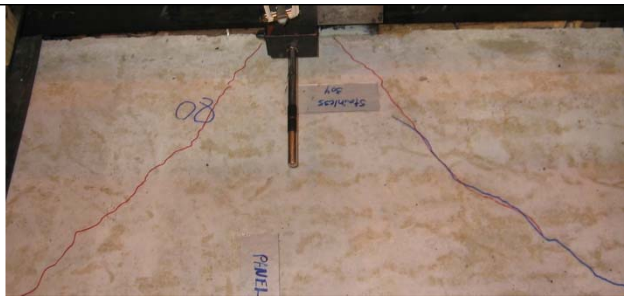


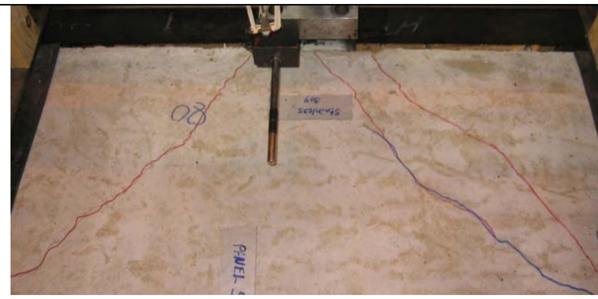
Figure 43: Shear force and displacement (Out-of-plane shear) E1

TEST E2: STAINLESS CONNECTION UNDER MONOTONIC OUT-OF-PLANE SHEAR (4-IN PANEL)

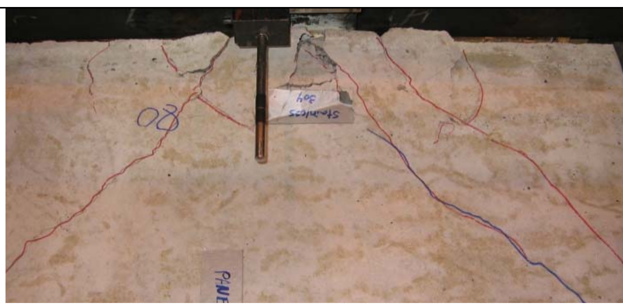
The performance of the Universal connection subject to monotonic, out-of-plane shear is presented in this section. The connector was subjected to shear displacement in the vertical direction with the in plane shear and tension displacements restrained. The performance of the panel was characterized by cracking and spalling in the area where the connector legs are embedded. Failure occurred when the connector legs had been pulled free of the surrounding concrete. The observed key events and the corresponding displacement level are presented in Table 20. The photos of the damage states are presented in Figure 44. The initial and final conditions of the specimen are presented in Figure 45 and Figure 46. The global force deformation response and backbone curve are presented in Table 21 and Figure 47.



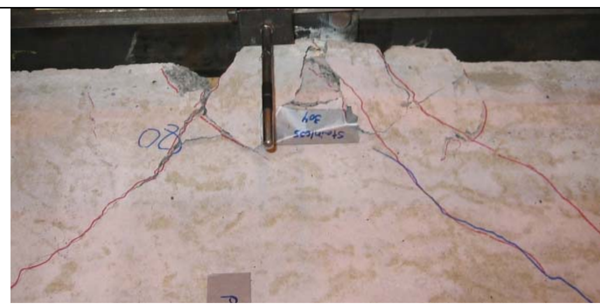
a) 0.09-in.



b) 0.32-in.



c) 0.87-in.



d) 2.37-in

Figure 44: Damage state at various out-of-plane shear deformations E2

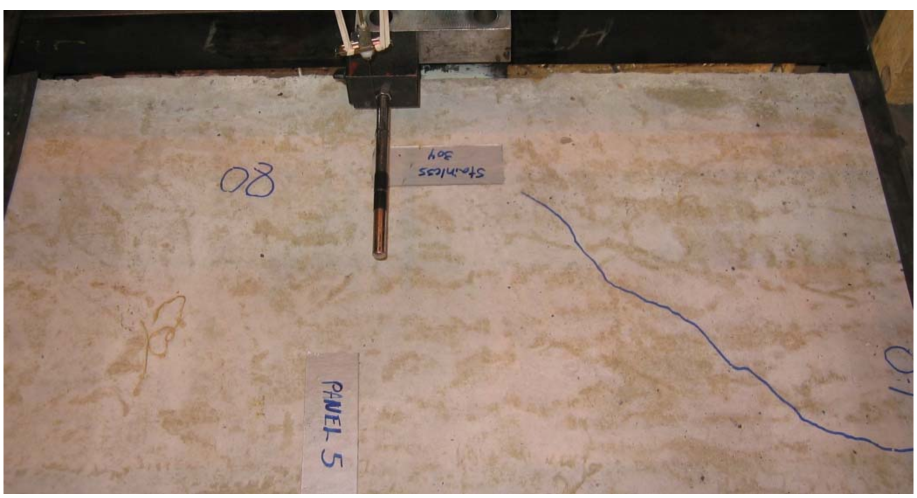


Figure 45: Initial condition of test E2


Figure 46: Final condition of test E2

Table 20: Key Test Observations (Out-of-plane shear) E2		
Event #	Shear Δ Step [in.]	Event Description
1	0.09	First two diagonal cracks formed on the panel
2	0.32	One more diagonal crack formed on right side of the panel
3	0.97	More small cracks formed around the connector, concrete started spalling
4	1.58	Concrete continued spalling
5	2.37	Connector sheared out of the panel

Table 21: Experimental Results Backbone Curve (Out-of-plane shear) E2		
Event	Shear Displacement [in.]	Shear Force [kips]
Peak Load	0.30	6.33
End of test	2.37	4.22

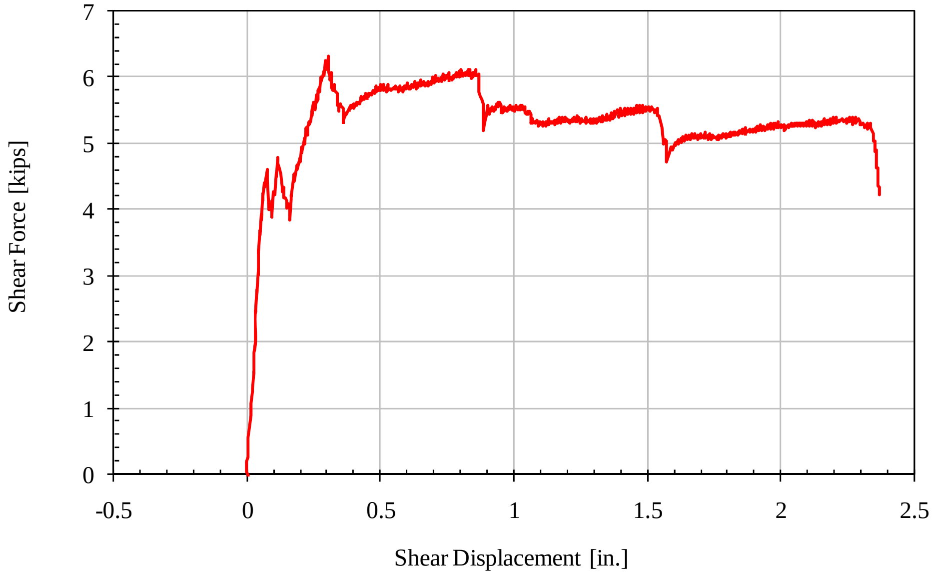


Figure 47: Shear force and displacement (Out-of-plane shear) E2

TEST A3: 1018 CONNECTION UNDER MONOTONIC IN-PLANE TENSION (2-IN PANEL)

The performance of the Universal connection subject to monotonic, in-plane tension is presented in this section. The connector was subjected to in plane tension displacement with the shear force unrestrained. Connector response was characterized by bending of the faceplate with application of tension. No damage was observed on the concrete surrounding the connection. The weld began to fracture on the tip of the slug at a tension displacement of 0.75 in. Loss in capacity occurred due to failure of the faceplate. The observed key events and the corresponding displacement level are presented in Table 22. The photos of the damage states are presented in Figure 48. The initial final conditions of the specimen are presented in Figure 49. The global force deformation response and backbone curve are presented in Table 23 and Figure 50.

a) Initial conditions

b) 0.38-in.

c) 0.42-in.

d) 0.42-in

Figure 48: Damage state at various In-plane tension deformations of test A3

Figure 49: Final condition of test A3

Table 22: Key Test Observations (In-plane tension) A3		
Event #	Tension Δ Step [in.]	Event Description
1	0.38	Faceplate bent and fracture of weld initialed at the tip
2	0.42	Faceplate fractured vertically

Table 23: Experimental Results Backbone Curve (In-plane tension) A3		
Event	Tension Displacement [in.]	Tension Force [kips]
Peak Load	0.37	5.38
End of test	0.49	0.30

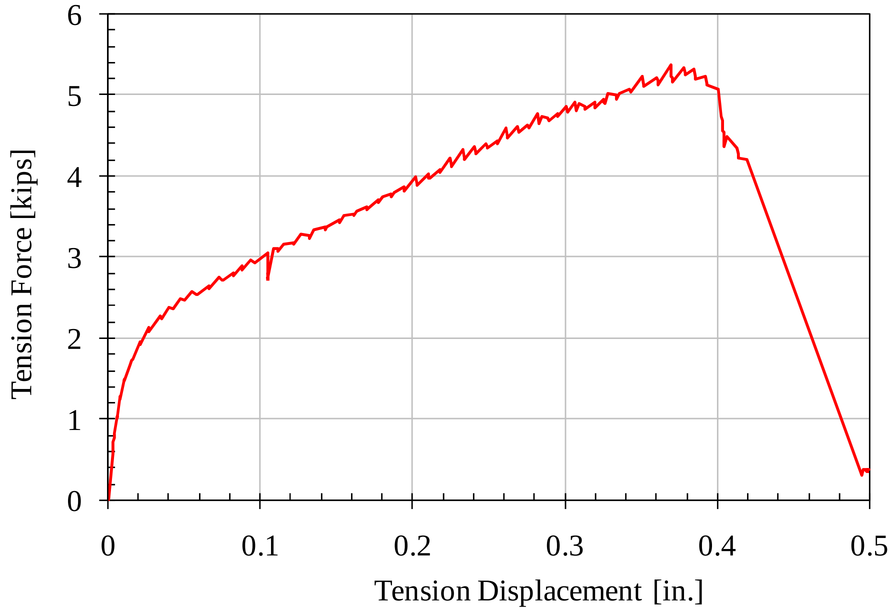


Figure 50: Tension force and displacement (In-plane tension) A3

TEST B3: STAINLESS CONNECTION UNDER MONOTONIC IN-PLANE TENSION (2-IN PANEL)

The performance of the Universal connection subject to monotonic, in-plane tension is presented in this section. The connector was subjected to in plane tension displacement with the shear force unrestrained. Connector response was characterized by bending of the faceplate with application of tension. The weld began to fracture on the tip of the slug at a tension displacement of 1.78 in. The test was conducted until the load cell was out of stroke. The observed key events and the corresponding displacement level are presented in Table 24. The photos of the damage states are presented in Figure 51. The initial final conditions of the specimen are presented in Figure 52. The global force deformation response and backbone curve are presented in Table 24 and Figure 53.

a) Initial conditions

b) 0.28-in.

c) 0.70-in.

d) 1.78-in

Figure 51: Damage state at various In-plane tension deformations of test B3

Figure 52: Final condition of test B3

Table 24: Key Test Observations (In-plane tension) B3		
Event #	Tension Δ Step [in.]	Event Description
1	0.28	Faceplate bending
2	0.70	One minor diagonal crack formed above the compression leg of connector
3	1.78	Faceplate was continually bent and fracture of weld initialed at the left tip
3	2.23	Load cell was out of stroke

Table 25: Experimental Results Backbone Curve (In-plane tension) B3		
Event	Tension Displacement [in.]	Tension Force [kips]
Peak Load	0.35	5.95
End of test	2.23	3.96

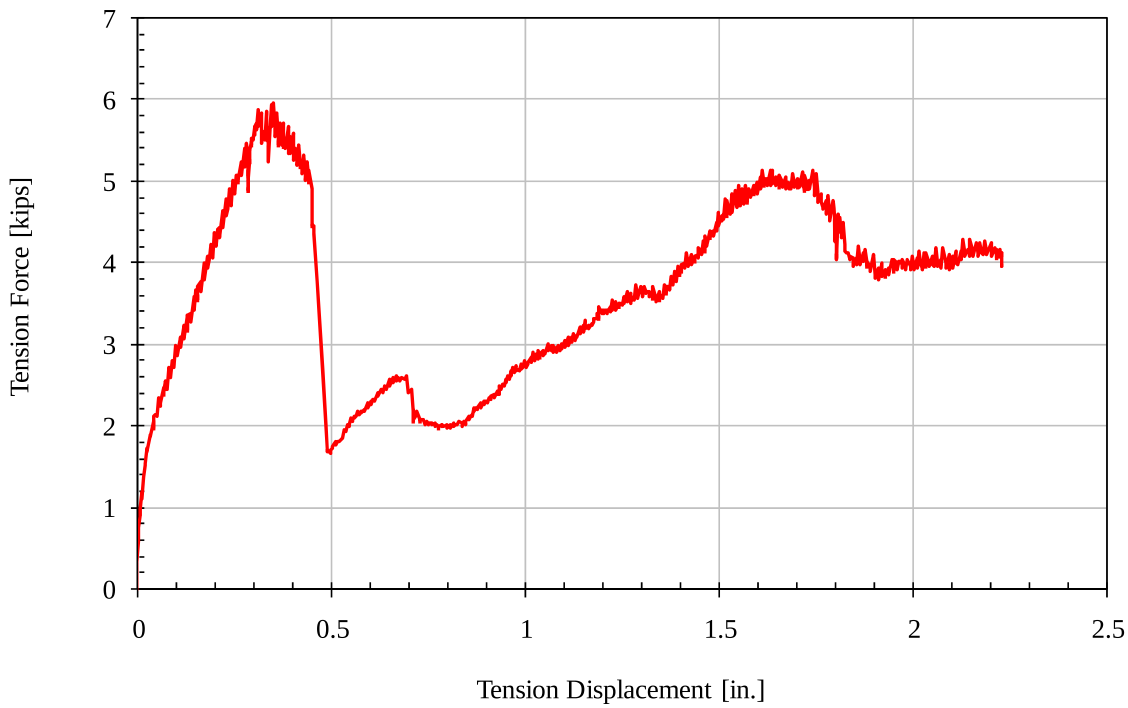
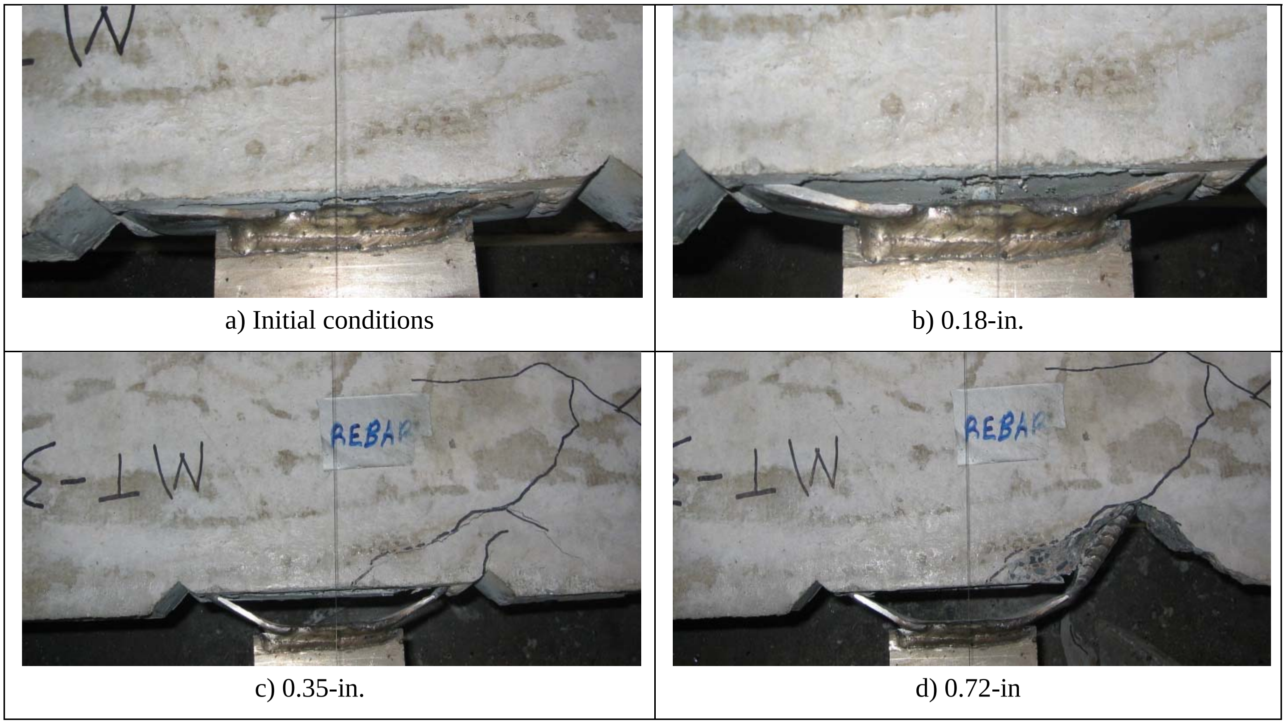


Figure 53: Tension force and displacement (In-plane tension) B3

TEST C1: REBAR CONNECTION UNDER MONOTONIC IN-PLANE TENSION (2-IN PANEL)

The performance of the Universal connection subject to monotonic, in-plane tension is presented in this section. The connector was subjected to in plane tension displacement with the shear force unrestrained. Connector response was characterized by bending of the faceplate and the concrete cracks around the connector leg with application of tension. Failure occurred due to the breakout of concrete surrounding the connector legs. The observed key events and the corresponding displacement level are presented in Table 26. The photos of the damage states are presented in Figure 54. The initial final conditions of the specimen are presented in Figure 55. The global force deformation response and backbone curve are presented in Table 27 and Figure 56.



a) Initial conditions

b) 0.18-in.

c) 0.35-in.

d) 0.72-in

Figure 54: Damage state at various In-plane tension deformations of test C1

Figure 55: Final condition of test C1

Table 26: Key Test Observations (In-plane tension) C1		
Event #	Tension Δ Step [in.]	Event Description
1	0.18	Faceplate bending
2	0.35	Cracks formed above the compression leg of connector; Faceplate was continually bent
3	0.72	Faceplate was continually bent; Concrete panel spalled
3	0.75	Concrete breakout around the right connector leg

Table 27: Experimental Results Backbone Curve (In-plane tension) C1		
Event	Tension Displacement [in.]	Tension Force [kips]
Peak Load	0.33	9.34
End of test	0.75	0.97

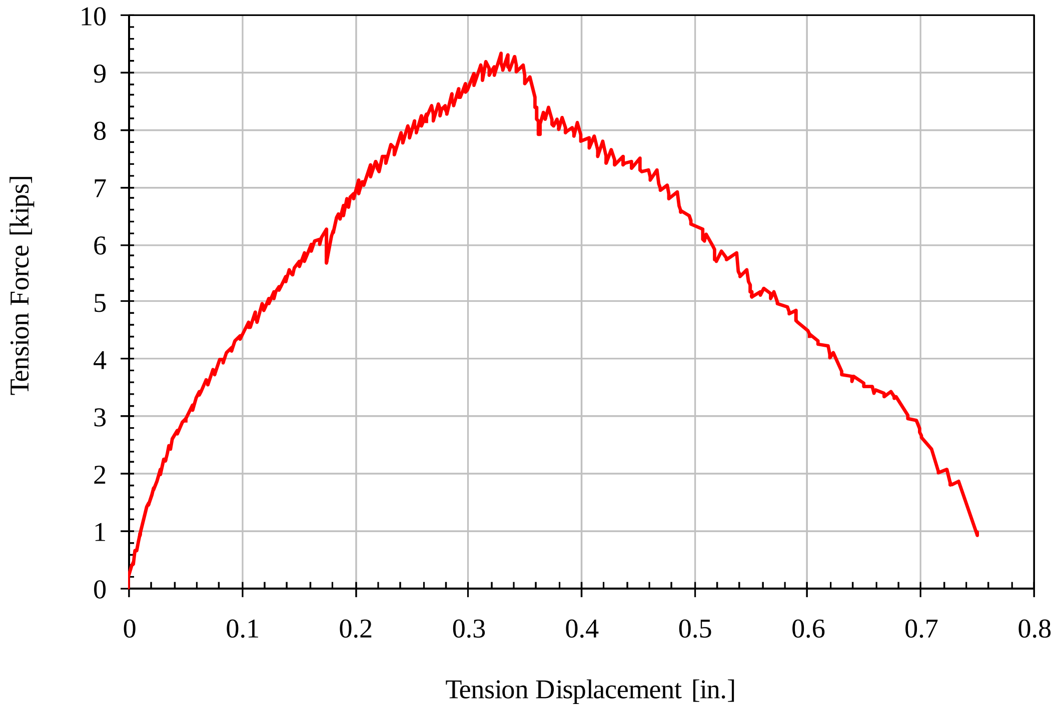


Figure 56: Tension force and displacement (In-plane tension) C1

TEST D3: 1018 CONNECTION UNDER MONOTONIC IN-PLANE TENSION (4-IN PANEL)

The performance of the Universal connection subject to monotonic, in-plane tension is presented in this section. The connector was subjected to in plane tension displacement with the shear force unrestrained. Connector response was characterized by bending of the faceplate with application of tension. No damage was observed on the concrete surrounding the connection. The weld began to fracture on the tip of the slug at a tension displacement of 0.46 in. Loss in capacity occurred due to failure of the faceplate. The observed key events and the corresponding displacement level are presented in Table 28. The photos of the damage states are presented in Figure 57. The initial final conditions of the specimen are presented in Figure 58. The global force deformation response and backbone curve are presented in Table 29 and Figure 59.

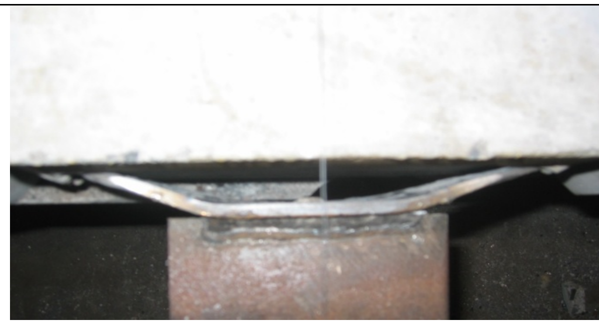
 a) Initial conditions	 b) 0.46-in.
 c) 0.64-in.	 d) 0.82-in

Figure 57: Damage state at various In-plane tension deformations of test D3

Figure 58: Final condition of test D3

Table 28: Key Test Observations (In-plane tension) D3		
Event #	Tension Δ Step [in.]	Event Description
1	0.46	Faceplate bending; weld began to fracture at the right tip
2	0.64	Faceplate yield and began to fracture, weld continually fractured
3	0.72	Faceplate continually fractured horizontally ;
4	0.82	Faceplate continually fractured horizontally ;
5	1.78	End of test

Table 29: Experimental Results Backbone Curve (In-plane tension) D3		
Event	Tension Displacement [in.]	Tension Force [kips]
Peak Load	0.45	8.99
End of test	1.78	0.42

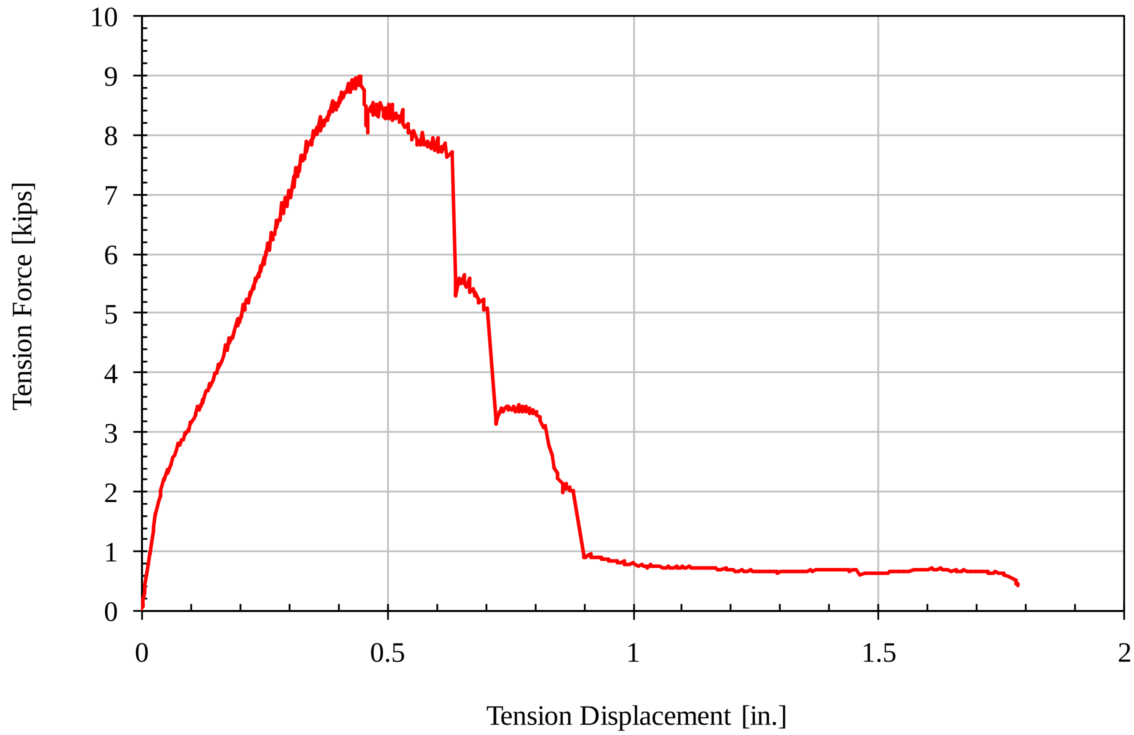


Figure 59: Tension force and displacement (In-plane tension) D3

TEST E3: STAINLESS CONNECTION UNDER MONOTONIC IN-PLANE TENSION (4-IN PANEL)

The performance of the Universal connection subject to monotonic, in-plane tension is presented in this section. The connector was subjected to in plane tension displacement with the shear force unrestrained. Connector response was characterized by bending of the faceplate with application of tension. No damage was observed on the concrete surrounding the connection. The weld began to fracture on the tip of the slug at a tension displacement of 0.61 in. Loss in capacity occurred due to failure of the faceplate. The observed key events and the corresponding displacement level are presented in Table 30. T he photos of the damage states are presented in Figure 60. The initial final conditions of the specimen are presented in Figure 61. The global force deformation response and backbone curve are presented in Table 31 and Figure 62.

 a) Initial conditions	 b) 0.61-in.
 c) 0.90-in.	 d) 1.15-in

Figure 60: Damage state at various In-plane tension deformations of test E3

Figure 61: Final condition of test E3

Table 30: Key Test Observations (In-plane tension) E3		
Event #	Tension Δ Step [in.]	Event Description
1	0.61	Faceplate bending; weld began to fracture at the left tip
2	0.90	Weld began to fracture at the right tip
3	1.15	Faceplate yield and began to fracture, weld continually fractured
4	2.41	Plate completely fractured

Table 31: Experimental Results Backbone Curve (In-plane tension) E3		
Event	Tension Displacement [in.]	Tension Force [kips]
Peak Load	0.59	14.36
End of test	2.41	1.45

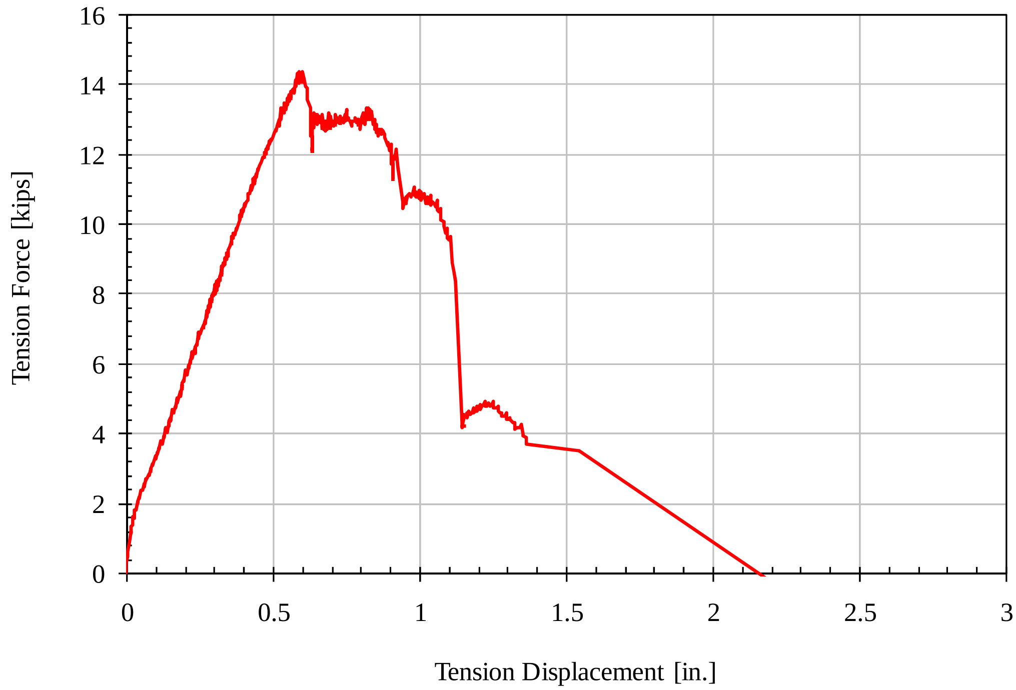
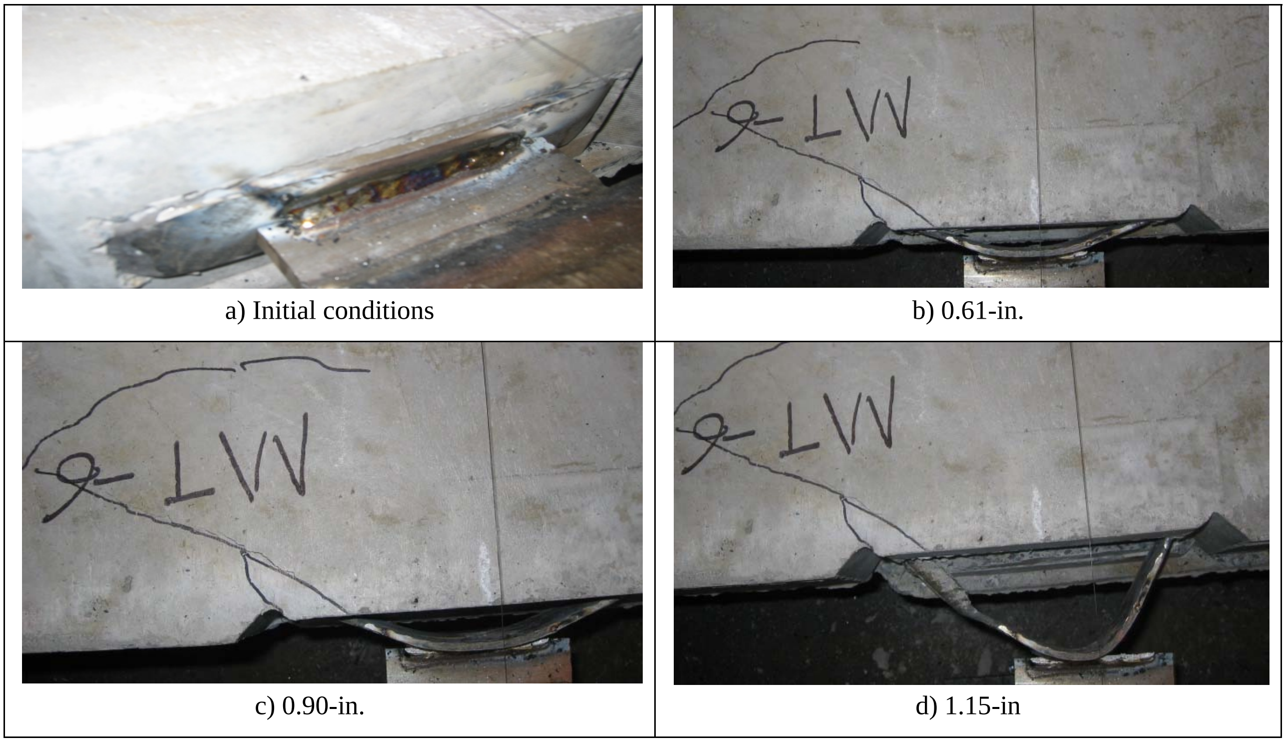


Figure 62: Tension force and displacement (In-plane tension) E3

TEST F1: REBAR CONNECTION UNDER MONOTONIC IN-PLANE TENSION (4-IN PANEL)

The performance of the Universal connection subject to monotonic, in-plane tension is presented in this section. The connector was subjected to in plane tension displacement with the shear force unrestrained. Connector response was characterized by bending of the faceplate and the concrete cracks around the connector leg with application of tension. The weld began to fracture on the tips of the slug at a tension displacement of 0.47 in. Failure occurred when the left connector leg was pulled out from the concrete. The observed key events and the corresponding displacement level are presented in Table 32. The photos of the damage states are presented in Figure 63. The initial final conditions of the specimen are presented in Figure 64. The global force deformation response and backbone curve are presented in Table 33 and Figure 65.



a) Initial conditions

b) 0.61-in.

c) 0.90-in.

d) 1.15-in

Figure 63: Damage state at various In-plane tension deformations of test F1

Figure 64: Final condition of test F1

Table 32: Key Test Observations (In-plane tension) F1		
Event #	Tension Δ Step [in.]	Event Description
1	0.47	Faceplate bending; weld began to fracture at the both tips; cracks formed on the panel above the tension leg of the connector.
2	0.61	Weld continually fractured, cracks extended
3	0.67	Weld continually fractured
4	1.55	Weld severely fractured; Tension leg was pulled out of the surrounding concrete
5	2.24	End of the test

Table 33: Experimental Results Backbone Curve (In-plane tension) F1		
Event	Tension Displacement [in.]	Tension Force [kips]
Peak Load	0.37	12.59
End of test	2.24	1.48

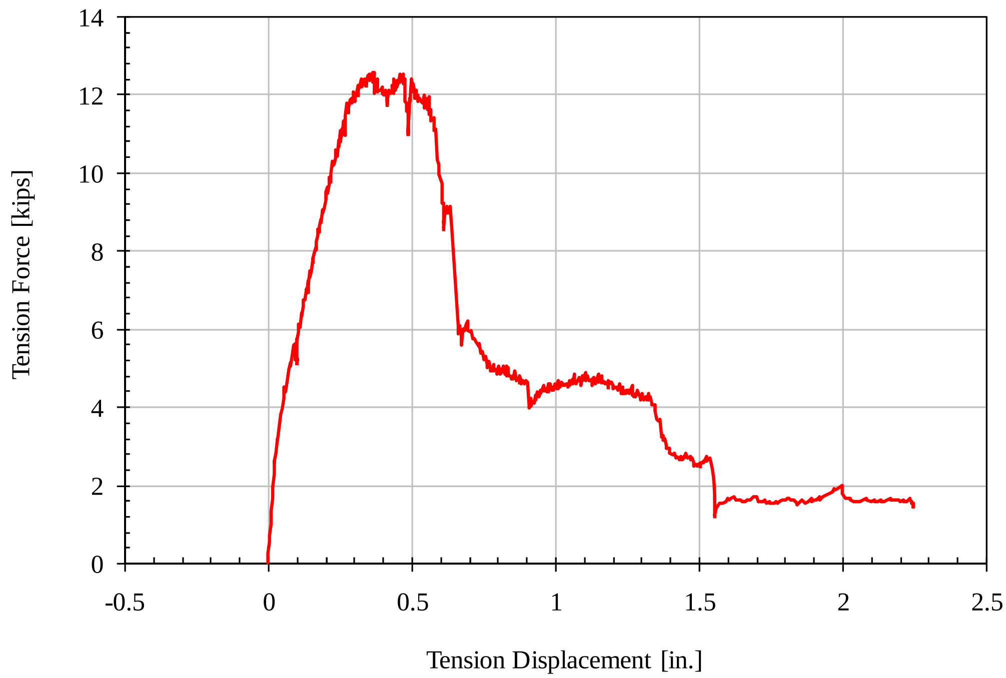


Figure 65: Tension force and displacement (In-plane tension) F1

TEST D5: 1018 CONNECTION UNDER MONOTONIC IN-PLANE SHEAR (4-IN PANEL)

The performance of the Universal connection subject to monotonic in-plane shear is presented in this section. The panel was subjected to shear displacement with the tension force unrestrained. Connector damage progression consisted of faceplate bending followed by faceplate fracture at the tip of weld between slug and faceplate. The ultimate loss in capacity occurred due to abrupt faceplate failure. The observed key events and the corresponding displacement level are presented in Table 34. The photos of the damage states are presented in Figure 66. The final condition of the specimen is presented in Figure 67. The global force deformation response and backbone curve are presented in Table 35 and Figure 68.

a) Initial conditions

b) 0.03-in.

Figure 66: Damage state at various In-plane shear deformations D5

Figure 67: Final condition of test D5

Table 34: Key Test Observations (In-plane shear) D5		
Event #	Shear Δ Step [in.]	Event Description
1	0.08	Plate bending
2	0.36	Faceplate fractured abruptly

Table 35: Experimental Results Backbone Curve (In-plane shear) D5		
Event	Shear Displacement [in.]	Shear Force [kips]
Peak Load	0.25	26.70
End of test	0.36	16.34

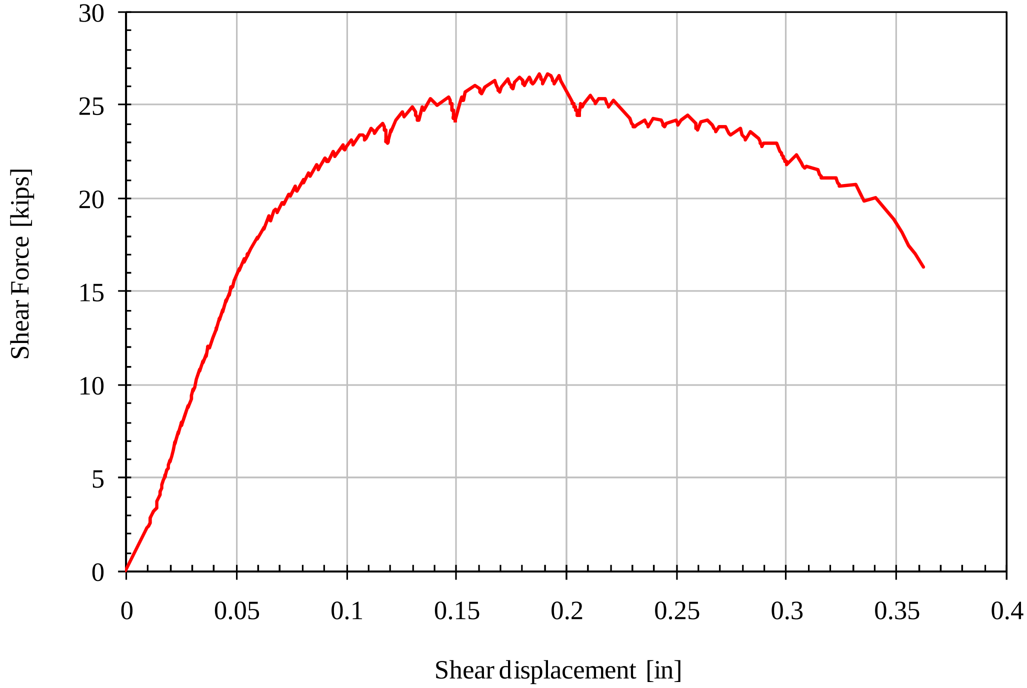


Figure 68: Shear force and displacement (In-plane shear) D5

TEST A5: 1018 CONNECTION UNDER MONOTONIC IN-PLANE SHEAR (2-IN PANEL)

The performance of the Universal connection subject to monotonic in-plane shear is presented in this section. The panel was subjected to shear displacement with the tension force unrestrained. Connector damage progression consisted of faceplate bending followed by bearing on the tension anchorage leg and concrete cracking above the connector legs. The ultimate loss in capacity occurred due to spalling above the anchorage legs of the connector. The observed key events and the corresponding displacement level are presented in Table 36. The photos of the damage states are presented in Figure 69. The final condition of the specimen is presented in Figure 70. The global force deformation response and backbone curve are presented in Table 37 and Figure 71.

a) Initial conditions

b) 0.27-in.

c) 0.75-in.

d) 1.49-in

Figure 69: Damage state at various In-plane shear deformations A5

Figure 70: Final condition of test A5

Table 36: Key Test Observations (In-plane shear) A5		
Event #	Shear Δ Step [in.]	Event Description
1	0.14	One minor crack formed on the right side of the panel
2	0.27	Crack progressed and small gap formed b/w panel and faceplate
3	0.75	Concrete Spalling above the compression leg; bending of connector legs
4	1.18	Concrete Spalling above both legs
3	1.49	Concrete sever Spalling above both legs; End of test

Table 37: Experimental Results Backbone Curve (In-plane shear) A5		
Event	Shear Displacement [in.]	Shear Force [kips]
Peak Load	0.28	17.53
End of test	1.49	2.35

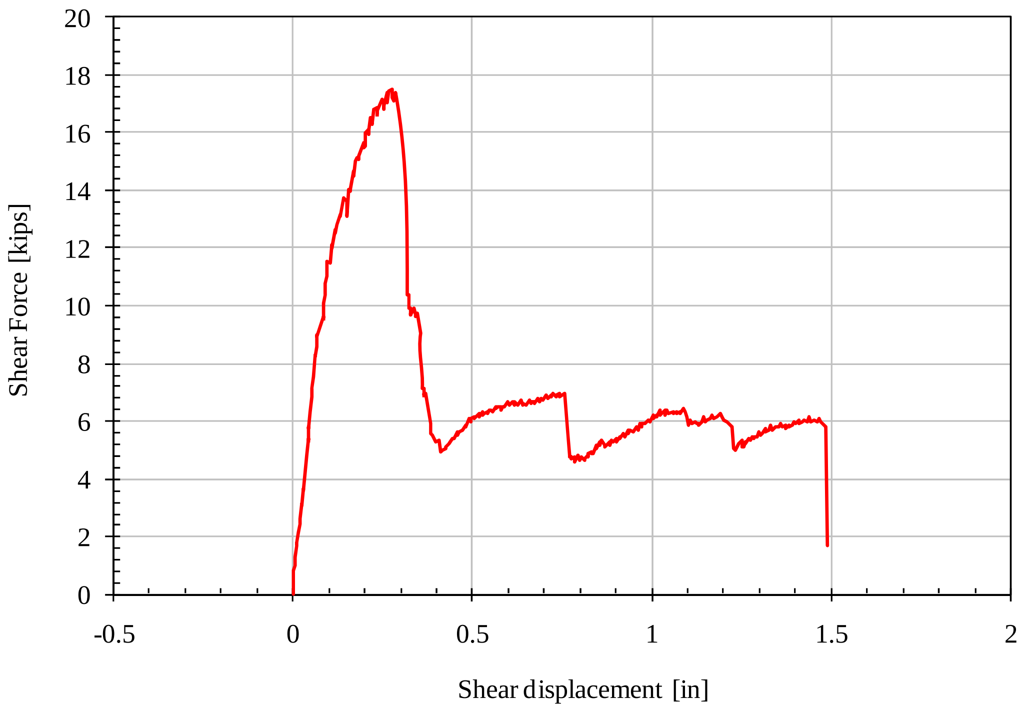
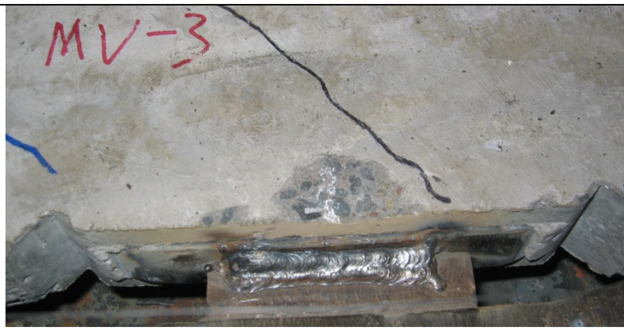


Figure 71: Shear force and displacement (In-plane shear) A5

TEST A4: 1018 CONNECTION UNDER MONOTONIC IN-PLANE SHEAR (2-IN PANEL)

The performance of the Universal connection subject to monotonic in-plane shear is presented in this section. The panel was subjected to shear displacement with the tension force unrestrained. Connector damage progression consisted of faceplate bending followed by bearing on the tension anchorage leg and concrete spalling around the connector legs. The ultimate loss in capacity occurred due to spalling above the compression anchorage leg and also below the tension anchorage leg of the connector. The observed key events and the corresponding displacement level are presented in Table 38. The photos of the damage states are presented in Figure 72. The final condition of the specimen is presented in Figure 73. The global force deformation response and backbone curve are presented in Table 39 and Figure 74.



a) Initial conditions

b) 0.43-in.

c) 0.90-in.

d) 1.01-in

Figure 72: Damage state at various In-plane shear deformations A4

Figure 73: Final condition of test A4

Table 38: Key Test Observations (In-plane shear) A4		
Event #	Shear Δ Step [in.]	Event Description
1	0.27	One minor crack formed on the right side of the panel
2	0.43	Small gap formed b/w panel and faceplate; Concrete Spalling above the compression leg
3	0.90	Bending of connector legs and faceplate; Concrete continually spalled
4	1.01	Concrete began to spall below the tension anchorage leg
5	1.19	Concrete sever spalling above both legs
6	2.34	End of test

Table 39: Experimental Results Backbone Curve (In-plane shear) A4		
Event	Shear Displacement [in.]	Shear Force [kips]
Peak Load	0.38	15.85
End of test	2.34	1.60

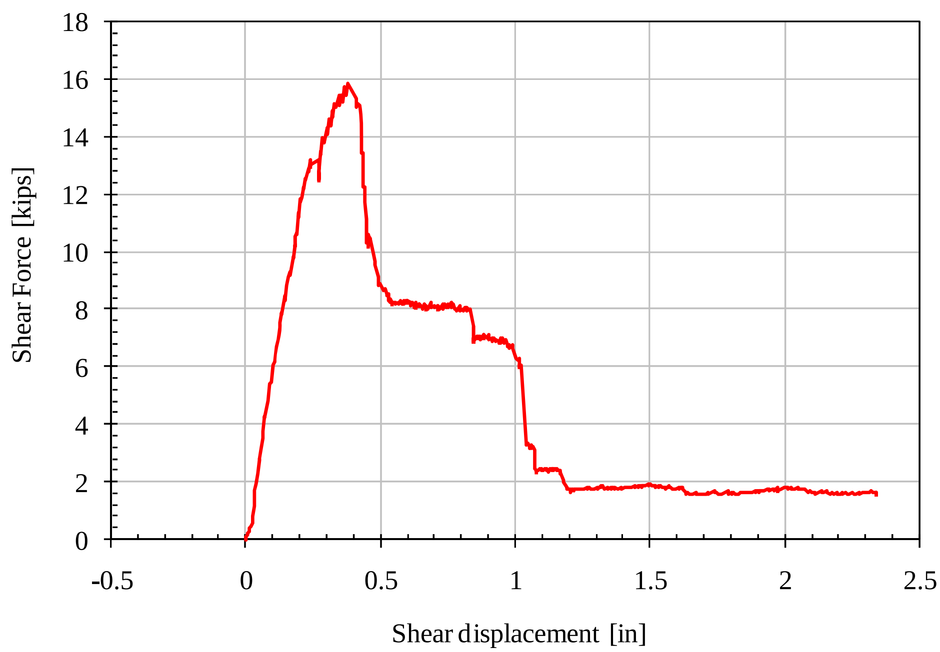


Figure 74: Shear force and displacement (In-plane shear) A4

TEST B5: STAINLESS CONNECTION UNDER MONOTONIC IN-PLANE SHEAR (2-IN PANEL)

The performance of the Universal connection subject to monotonic in-plane shear is presented in this section. The panel was subjected to shear displacement with the tension force unrestrained. Connector damage progression consisted of faceplate bending followed by bearing on the tension anchorage leg and concrete spalling around the connector legs. The ultimate loss in capacity occurred due to spalling above the compression and tension anchorage legs of the connector. The observed key events and the corresponding displacement level are presented in Table 40. The photos of the damage states are presented in Figure 75. The final condition of the specimen is presented in Figure 76. The global force deformation response and backbone curve are presented in Table 41 and Figure 77.

a) Initial conditions

b) 0.33-in.

c) 0.45-in.

d) 1.32-in

Figure 75: Damage state at various In-plane shear deformations B5

Figure 76: Final condition of test B5

Table 40: Key Test Observations (In-plane shear) B5		
Event #	Shear Δ Step [in.]	Event Description
1	0.33	One minor crack formed on left side of the panel; Faceplate bending; Concrete spalling above the compression leg
2	0.45	Bending of connector legs and faceplate; Concrete Spalling above the tension leg
3	1.32	Concrete continually spalled
6	2.28	End of test

Table 41: Experimental Results Backbone Curve (In-plane shear) B5		
Event	Shear Displacement [in.]	Shear Force [kips]
Peak Load	0.30	16.47
End of test	2.28	6.46

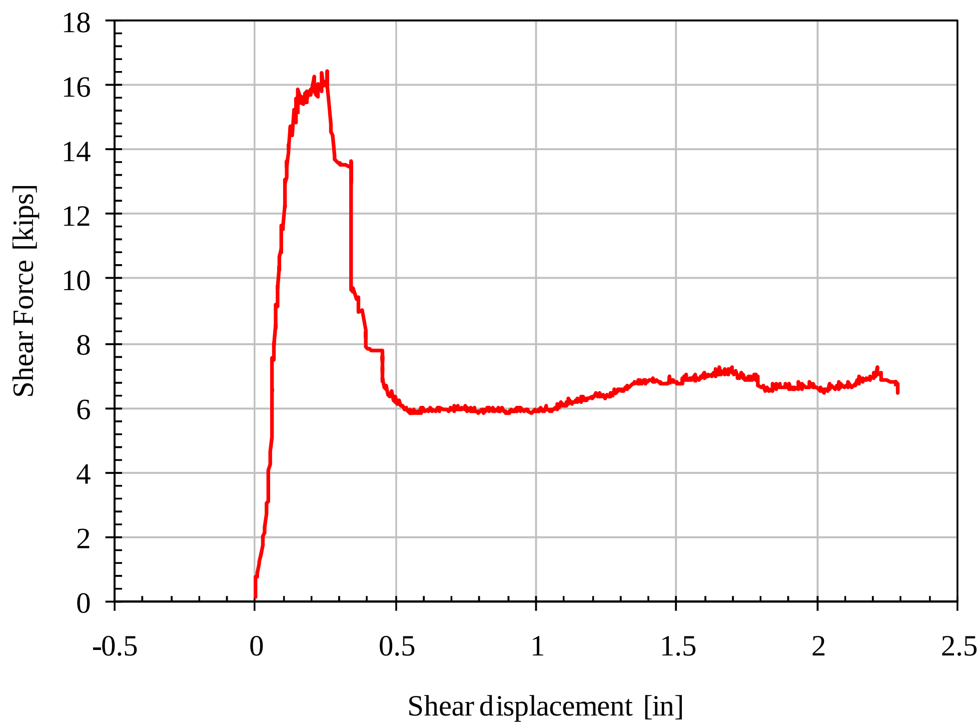


Figure 77: Shear force and displacement (In-plane shear) B5

TEST C2: REBAR CONNECTION UNDER MONOTONIC IN-PLANE SHEAR (2-IN PANEL)

The performance of the Universal connection subject to monotonic in-plane shear is presented in this section. The panel was subjected to shear displacement with the tension force unrestrained. Connector damage progression consisted of faceplate bending followed by bearing on the tension anchorage leg and concrete spalling around the connector legs. The ultimate loss in capacity occurred due to spalling and separation of the left anchorage leg from the surrounding concrete. The observed key events and the corresponding displacement level are presented in Table 42. The photos of the damage states are presented in Figure 78. The final condition of the specimen is presented in Figure 79. The global force deformation response and backbone curve are presented in Table 43 and Figure 80.

a) Initial conditions

b) 0.26-in.

c) 0.31-in.

d) 1.20-in

Figure 78: Damage state at various In-plane shear deformations C2

Figure 79: Final condition of test C2

Table 42: Key Test Observations (In-plane shear) C2

Event #	Shear Δ Step [in.]	Event Description
1	0.26	Cracks formed on left side of the panel; Faceplate bending; Concrete spalling around the faceplate
2	0.31	Bending of connector legs and faceplate; Concrete began to spall below the tension leg; Existing spalling extended
3	1.20	Concrete continually spalled; Separation of the left anchorage leg from the surrounding concrete
6	1.21	End of test

Table 43: Experimental Results Backbone Curve (In-plane shear) C2		
Event	Shear Displacement [in.]	Shear Force [kips]
Peak Load	0.17	18.96
End of test	1.21	1.02

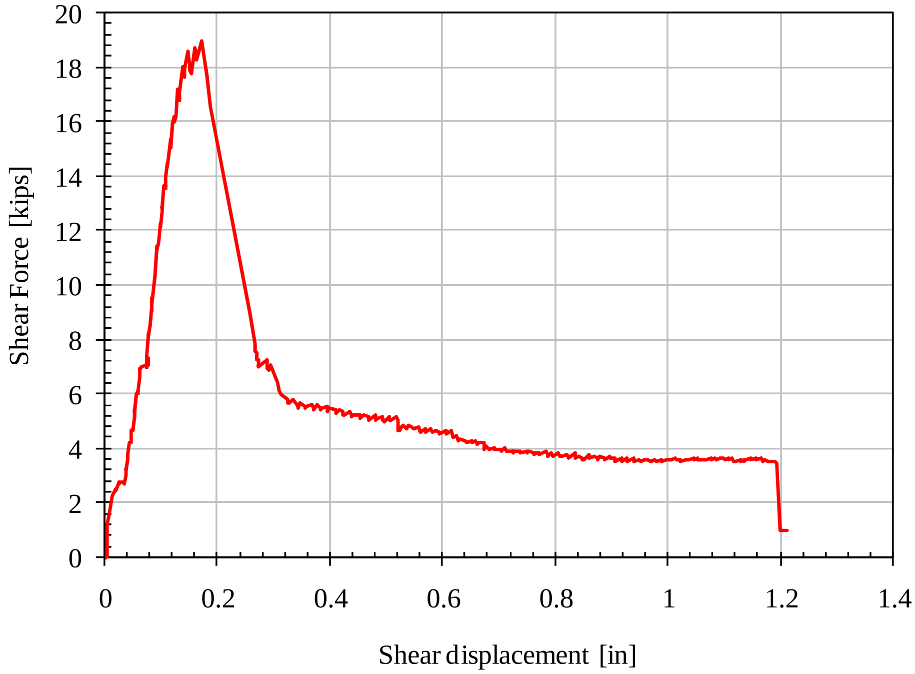


Figure 80: Shear force and displacement (In-plane shear) C2

TEST B4: STAINLESS CONNECTION UNDER MONOTONIC IN-PLANE SHEAR (2-IN PANEL)

The performance of the Universal connection subject to monotonic in-plane shear is presented in this section. The panel was subjected to shear displacement with the tension force unrestrained. Connector damage progression consisted of faceplate bending followed by bearing on the tension anchorage leg and concrete spalling around the connector legs. The ultimate loss in capacity occurred due to spalling above and below the compression and tension anchorage legs of the connector. The observed key events and the corresponding displacement level are presented in Table 44. The photos of the damage states are presented in Figure 81. The final condition of the specimen is presented in Figure 82. The global force deformation response and backbone curve are presented in Table 45 and Figure 83.

a) Initial conditions

b) 0.44-in.

c) 1.04-in.

d) 1.55-in

Figure 81: Damage state at various In-plane shear deformations B4

Figure 82: Final condition of test B4

Table 44: Key Test Observations (In-plane shear) B4		
Event #	Shear Δ Step [in.]	Event Description
1	0.44	Faceplate bending; Concrete spalling above the compression leg
2	1.04	Bending of connector legs and faceplate; Crack formed above the tension leg; Concrete began to spall below the tension leg
3	1.55	Concrete continually spalled; Separation of the left anchorage leg from the surrounding concrete
6	1.80	End of test

Table 45: Experimental Results Backbone Curve (In-plane shear) B4		
Event	Shear Displacement [in.]	Shear Force [kips]
Peak Load	0.23	13.87
End of test	1.80	0.25

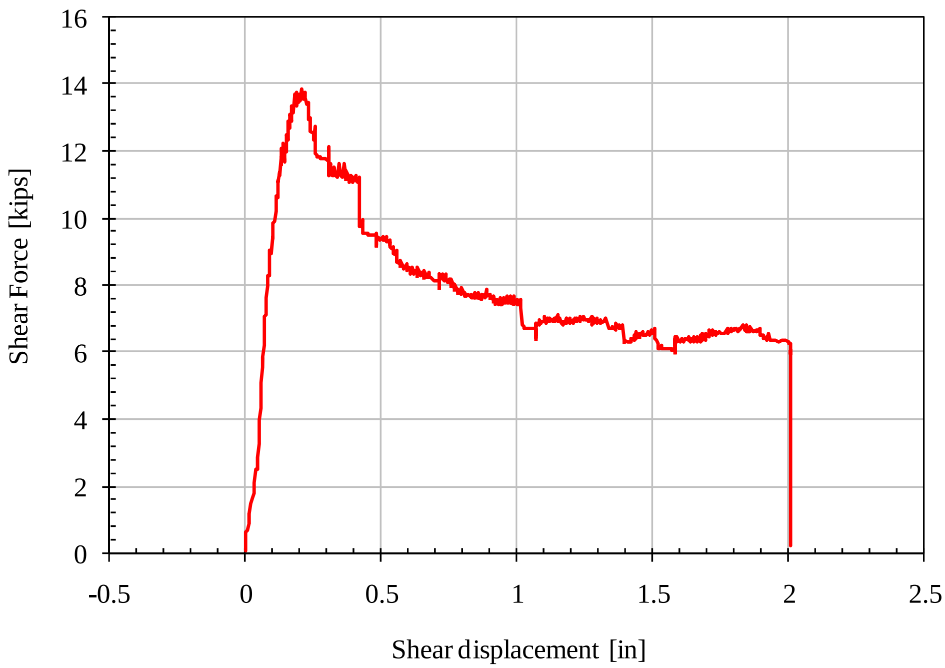


Figure 83: Shear force and displacement (In-plane shear) B4

TEST D4: 1018 CONNECTION UNDER MONOTONIC IN-PLANE SHEAR (4-IN PANEL)

The performance of the Universal connection subject to monotonic in-plane shear is presented in this section. The panel was subjected to shear displacement with the tension force unrestrained. Connector damage progression consisted of faceplate bending followed by faceplate fracture at the tip of weld between slug and faceplate. The ultimate loss in capacity occurred due to abrupt faceplate failure. The observed key events and the corresponding displacement level are presented in Table 46. The photos of the damage states are presented in Figure 84. The final condition of the specimen is presented in Figure 85. The global force deformation response and backbone curve are presented in Table 47 and Figure 86.

a) Initial conditions b) 0.45-in.

Figure 84: Damage state at various In-plane shear deformations D4

Figure 85: Final condition of test D4

Table 46: Key Test Observations (In-plane shear) D4		
Event #	Shear Δ Step [in.]	Event Description
1	0.45	Faceplate bent and fractured abruptly

Table 47: Experimental Results Backbone Curve (In-plane shear) D4		
Event	Shear Displacement [in.]	Shear Force [kips]
Peak Load	0.30	29.23
End of test	0.45	1.76

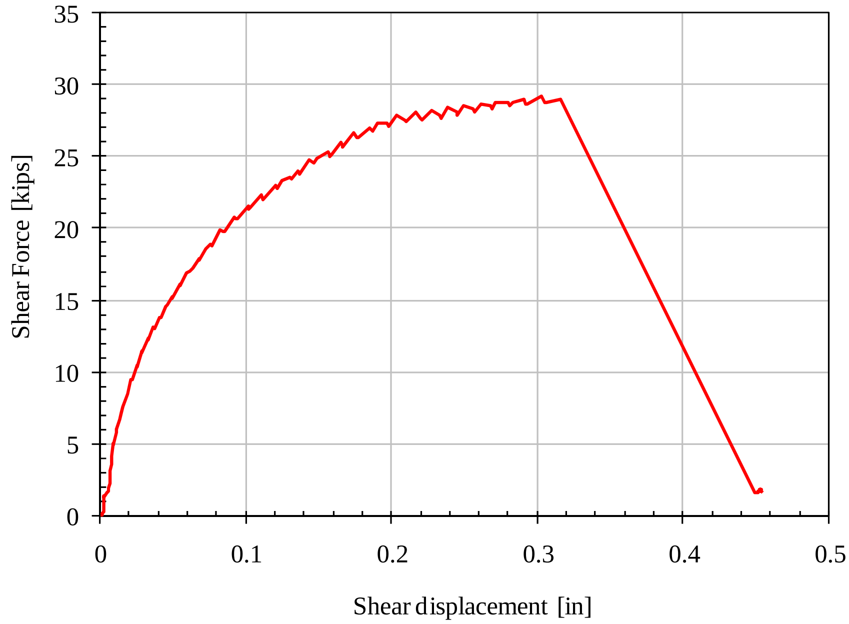


Figure 86: Shear force and displacement (In-plane shear) D4

Test E4: Stainless Connection Under Monotonic In-Plane SHEAR (4-in Panel)

The performance of the Universal connection subject to monotonic in-plane shear is presented in this section. The panel was subjected to shear displacement with the tension force unrestrained. Connector damage progression consisted of faceplate bending followed by bearing on the tension anchorage leg and concrete cracks and spalling around the connector legs. The test was conducted until the load cell was out of stroke. The observed key events and the corresponding displacement level are presented in Table 48. The photos of the damage states are presented in Figure 87. The final condition of the specimen is presented in Figure 88. The global force deformation response and backbone curve are presented in Table 49 and Figure 89.

a) Initial conditions

b) 0.73-in.

c) 1.38-in.

d) 2.00-in

Figure 87: Damage state at various In-plane shear deformations E4

Figure 88: Final condition of test E4

Table 48: Key Test Observations (In-plane shear) E4		
Event #	Shear Δ Step [in.]	Event Description
1	0.73	Faceplate bending; Crack formed above the tension leg on the panel; Concrete spalling around the compression leg
2	1.38	Bending of connector legs and faceplate; Concrete continually spalled above the connector
3	2.00	Concrete continually spalled
6	2.14	End of test

Table 49: Experimental Results Backbone Curve (In-plane shear) E4		
Event	Shear Displacement [in.]	Shear Force [kips]
Peak Load	0.64	29.00
End of test	2.14	13.92

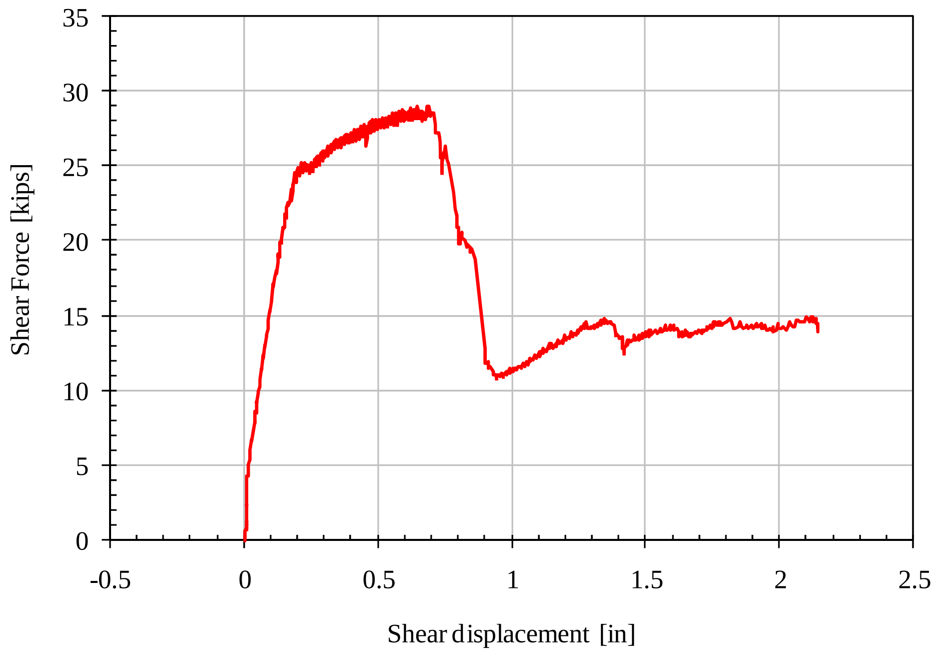


Figure 89: Shear force and displacement (In-plane shear) E4

TEST F2: REBAR CONNECTION UNDER MONOTONIC IN-PLANE SHEAR (4-IN PANEL)

The performance of the Universal connection subject to monotonic in-plane shear is presented in this section. The panel was subjected to shear displacement with the tension force unrestrained. Connector damage progression consisted of faceplate bending followed by bearing on the tension anchorage leg and concrete spalling around the connector legs. The ultimate loss in capacity occurred due to separation of the left anchorage leg from the surrounding concrete. The observed key events and the corresponding displacement level are presented in Table 50. The photos of the damage states are presented in Figure 90. The final condition of the specimen is presented in Figure 91. The global force deformation response and backbone curve are presented in Table 51 and Figure 92.

a) Initial conditions

b) 0.26-in.

c) 0.40-in.

d) 1.29-in

Figure 90: Damage state at various In-plane shear deformations F2

Figure 91: Final condition of test F2

Table 50: Key Test Observations (In-plane shear) F2		
Event #	Shear Δ Step [in.]	Event Description
1	0.26	Faceplate bending; Crack formed above the tension leg on the panel
2	0.32	Small crack formed around tension leg on the joint face
3	0.40	Bending of connector legs and faceplate; Concrete spalling above the tension leg of connector; Existing cracks progressed
4	1.29	Concrete continually spalled; Tension leg was pull out of the panel
6	2.19	End of test

Table 51: Experimental Results Backbone Curve (In-plane shear) F2		
Event	Shear Displacement [in.]	Shear Force [kips]
Peak Load	0.21	32.67
End of test	2.19	1.47

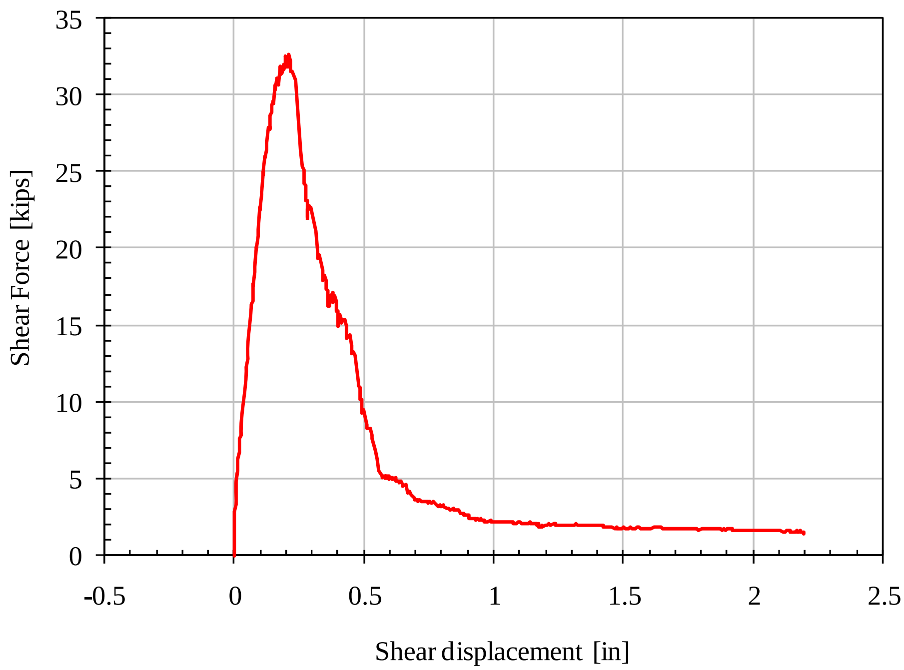


Figure 92: Shear force and displacement (In-plane shear) F2

TEST E5: STAINLESS CONNECTION UNDER MONOTONIC IN-PLANE SHEAR (4-IN PANEL)

The performance of the Universal connection subject to monotonic in-plane shear is presented in this section. The panel was subjected to shear displacement with the tension force unrestrained. Connector damage progression consisted of faceplate bending followed by bearing on the tension anchorage leg and concrete spalling around the connector legs. The test was conducted until the load cell was out of stroke. The observed key events and the corresponding displacement level are presented in Table 52. The photos of the damage states are presented in Figure 93. The final condition of the specimen is presented in Figure 94. The global force deformation response and backbone curve are presented in Table 53 and Figure 95.

a) Initial conditions

b) 0.12-in.

c)1.27-in.

d) 2.23-in

Figure 93: Damage state at various In-plane shear deformations E5

Figure 94: Final condition of test E5

Table 52: Key Test Observations (In-plane shear) E5		
Event #	Shear Δ Step [in.]	Event Description
1	0.12	Faceplate bending
2	0.59	Small spalling formed around compression leg on the joint face
3	1.27	Bending of connector legs and faceplate; Concrete spalling above the connector legs
4	2.10	Concrete continually spalled
6	2.23	End of test

Table 53: Experimental Results Backbone Curve (In-plane shear) E5		
Event	Shear Displacement [in.]	Shear Force [kips]
Peak Load	0.55	27.92
End of test	2.23	11.89

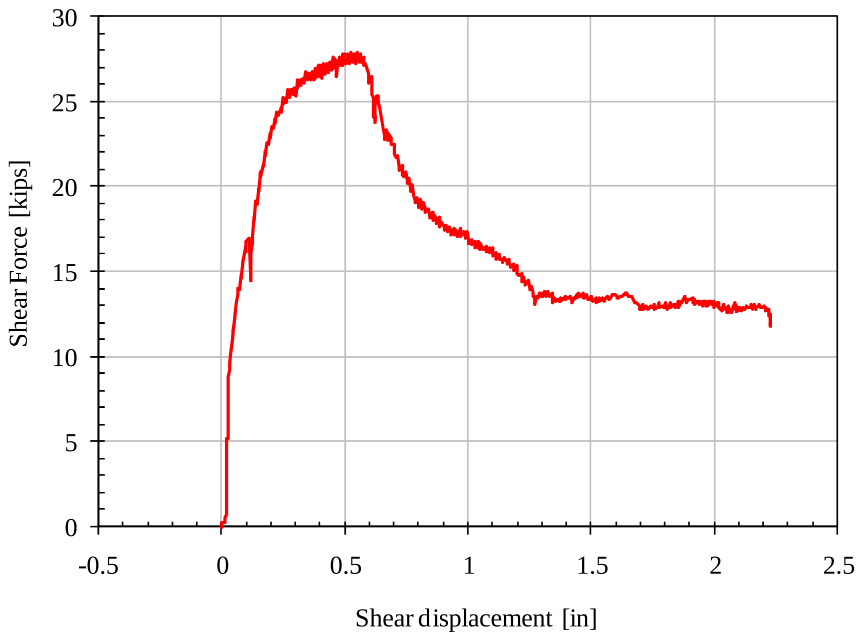


Figure 95: Shear force and displacement (In-plane shear) E5

TEST H1: ASTM A36 CONNECTION UNDER MONOTONIC IN-PLANE SHEAR (4-IN PANEL)

The performance of the Universal ASTM A36 connection subject to monotonic in-plane shear is presented in this section. The panel was subjected to shear displacement with the tension force unrestrained. Connector damage progression consisted of faceplate bending followed by faceplate fracture near where they become embedded in the concrete. The ultimate loss in capacity occurred due to abrupt faceplate failure. The observed key events and the corresponding displacement level are presented in Table 54. The photos of the damage states are presented in Figure 96. The final condition of the specimen is presented in Figure 97. The global force deformation response and backbone curve are presented in Table 55 and Figure 98.

a) Initial conditions

b) 0.13-in.

Figure 96: Damage state at various In-plane shear deformations H1

Figure 97: Final condition of test H1

Table 54: Key Test Observations (In-plane shear) H1		
Event #	Shear Δ Step [in.]	Event Description
1	0.13	Plate bending
2	0.65	Faceplate fractured abruptly

Table 55: Experimental Results Backbone Curve (In-plane shear) H1		
Event	Shear Displacement [in.]	Shear Force [kips]
Peak Load	0.43	27.93
End of test	0.95	0.60

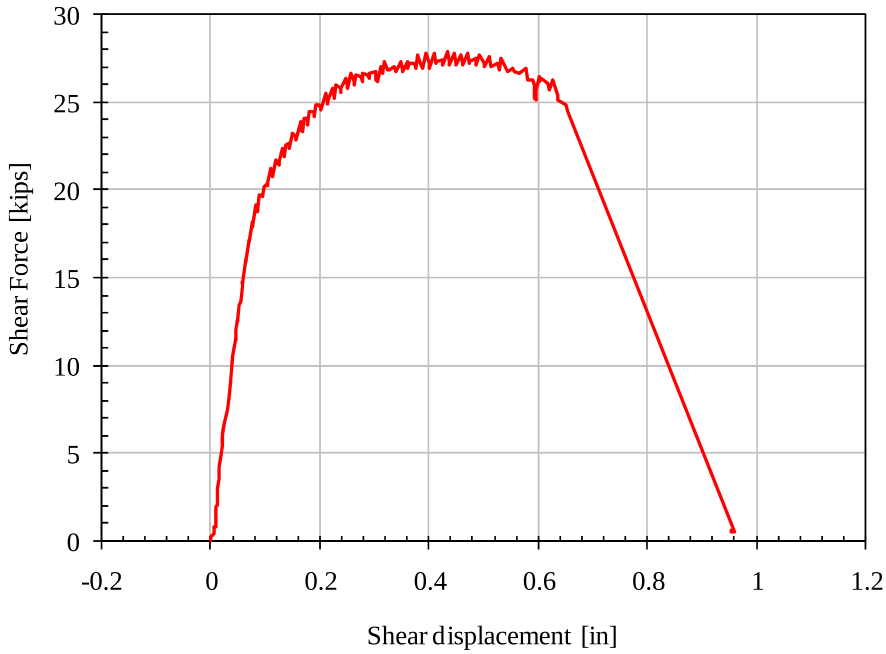
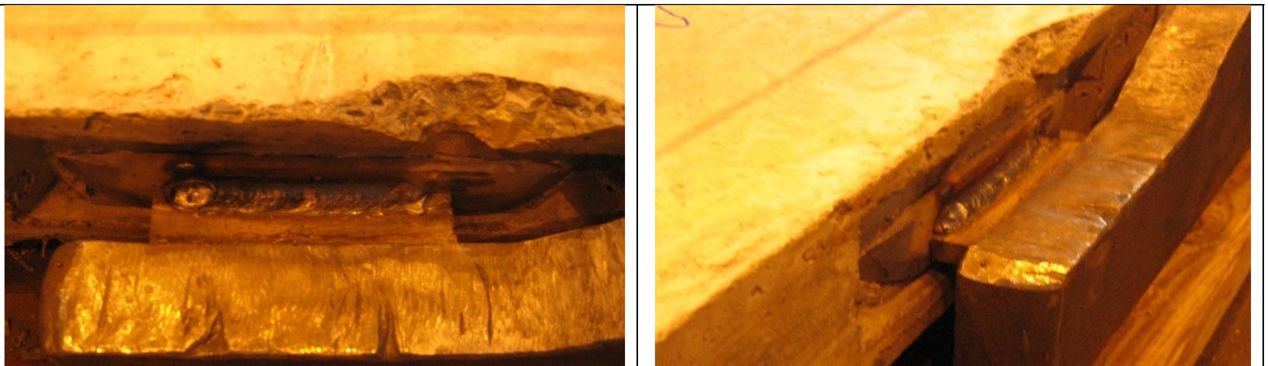


Figure 98: Shear force and displacement (In-plane shear) H1

TEST H2: ASTM A36 CONNECTION UNDER MONOTONIC IN-PLANE SHEAR (4-IN PANEL)

The performance of the Universal ASTM A36 connection subject to monotonic in-plane shear is presented in this section. The panel was subjected to shear displacement with the tension force unrestrained. Connector damage progression consisted of faceplate bending followed by faceplate fracture near where they become embedded in the concrete. The ultimate loss in capacity occurred due to abrupt faceplate failure. The observed key events and the corresponding displacement level are presented in Table 56. The photos of the damage states are presented in Figure 99. The final condition of the specimen is presented in Figure 100. The global force deformation response and backbone curve are presented in Table 57 and Figure 101.



a) Initial conditions

b) 0.14-in.

Figure 99: Damage state at various In-plane shear deformations H2

Figure 100: Final condition of test H2

Table 56: Key Test Observations (In-plane shear) H2

Event #	Shear Δ Step [in.]	Event Description
1	0.14	Plate bending
2	0.63	Faceplate fractured abruptly

Table 57: Experimental Results Backbone Curve (In-plane shear) H2

Event	Shear Displacement [in.]	Shear Force [kips]
Peak Load	0.46	27.42
End of test	0.78	0.85

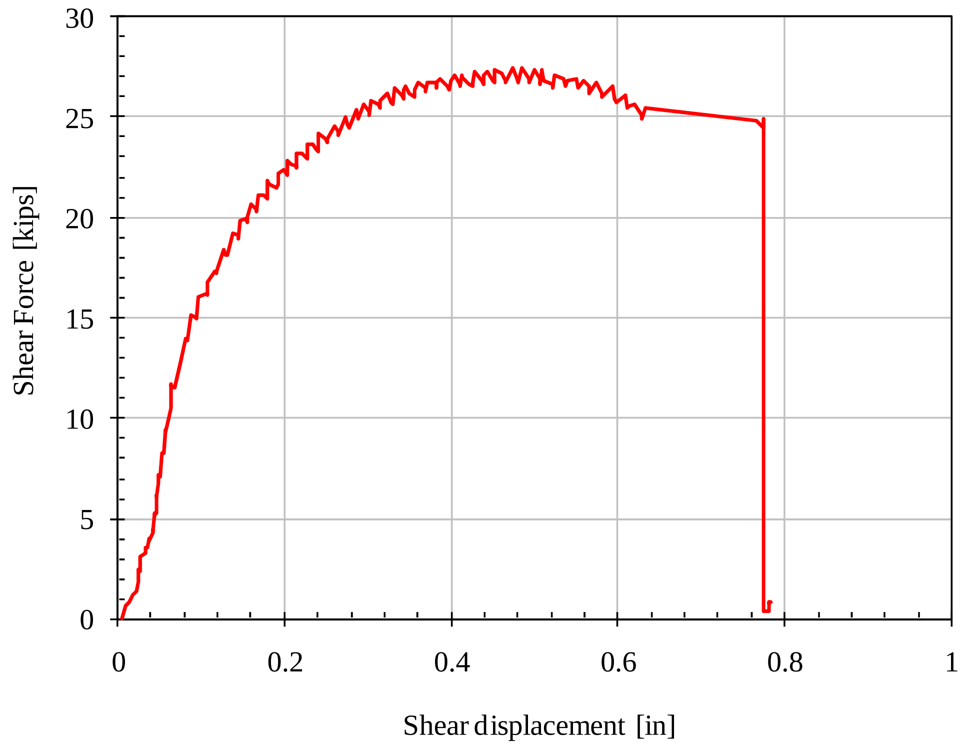
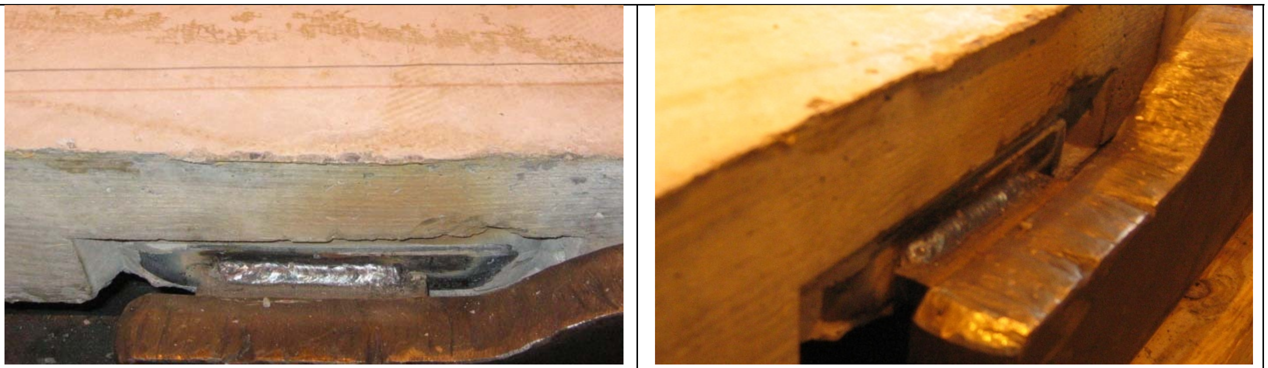


Figure 101: Shear force and displacement (In-plane shear) H2

TEST G1: ASTM A36 CONNECTION UNDER MONOTONIC IN-PLANE SHEAR (4-IN PANEL)

The performance of the Universal ASTM A36 connection subject to monotonic in-plane shear is presented in this section. The panel was subjected to shear displacement with the tension force unrestrained. Connector damage progression consisted of faceplate bending followed by faceplate fracture near where they become embedded in the concrete. The ultimate loss in capacity occurred due to abrupt faceplate failure. The observed key events and the corresponding displacement level are presented in Table 58. The photos of the damage states are presented in Figure 102. The final condition of the specimen is presented in Figure 103. The global force deformation response and backbone curve are presented in Table 59 and Figure 104.



a) Initial conditions

b) 0.16-in.

Figure 102: Damage state at various In-plane shear deformations G1

Figure 103: Final condition of test G1

Table 58: Key Test Observations (In-plane shear) G1

Event #	Shear Δ Step [in.]	Event Description
1	0.16	Plate bending
2	0.57	Faceplate fractured abruptly

Table 59: Experimental Results Backbone Curve (In-plane shear) G1

Event	Shear Displacement [in.]	Shear Force [kips]
Peak Load	0.39	16.21
End of test	0.78	0

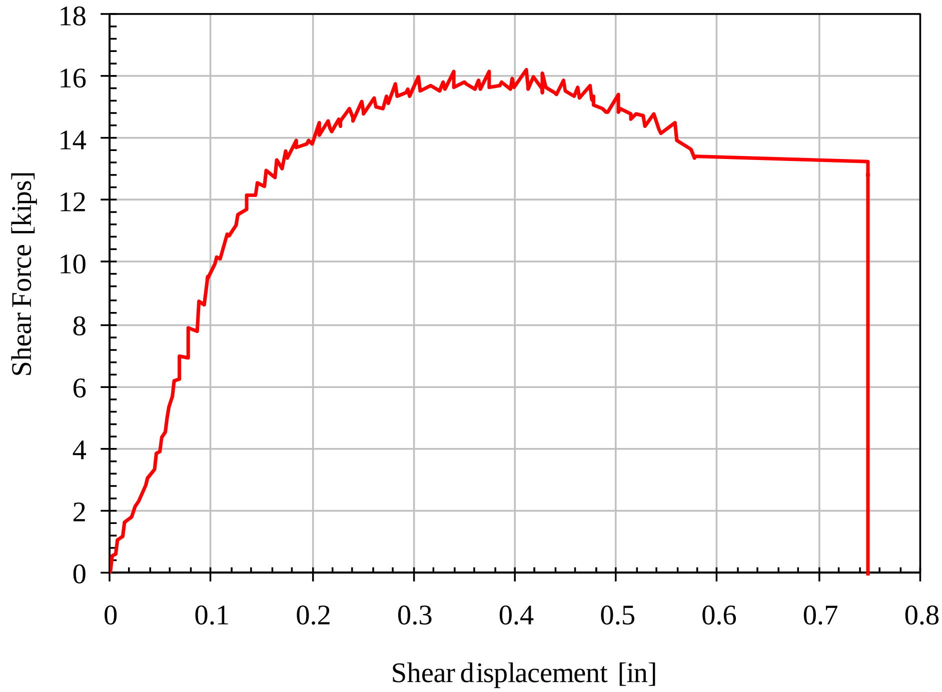
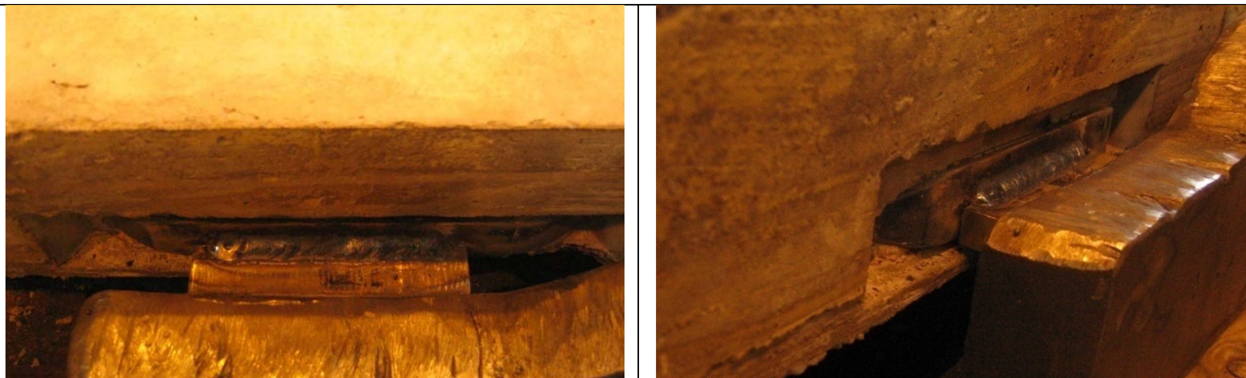


Figure 104: Shear force and displacement (In-plane shear) G1

TEST G2: ASTM A36 CONNECTION UNDER MONOTONIC IN-PLANE SHEAR (4-IN PANEL)

The performance of the Universal ASTM A36 connection subject to monotonic in-plane shear is presented in this section. The panel was subjected to shear displacement with the tension force unrestrained. Connector damage progression consisted of faceplate bending followed by faceplate fracture near where they become embedded in the concrete. The ultimate loss in capacity occurred due to abrupt faceplate failure. The observed key events and the corresponding displacement level are presented in Table 60. The photos of the damage states are presented in Figure 105. The final condition of the specimen is presented in Figure 106. The global force deformation response and backbone curve are presented in Table 61 and Figure 107.



a) Initial conditions

b) 0.16-in.

Figure 105: Damage state at various In-plane shear deformations G2

Figure 106: Final condition of test G2

Table 60: Key Test Observations (In-plane shear) G2

Event #	Shear Δ Step [in.]	Event Description
1	0.16	Plate bending
2	0.50	Faceplate fractured abruptly

Table 61: Experimental Results Backbone Curve (In-plane shear) G2

Event	Shear Displacement [in.]	Shear Force [kips]
Peak Load	0.32	16.82

End of test	0.60	0

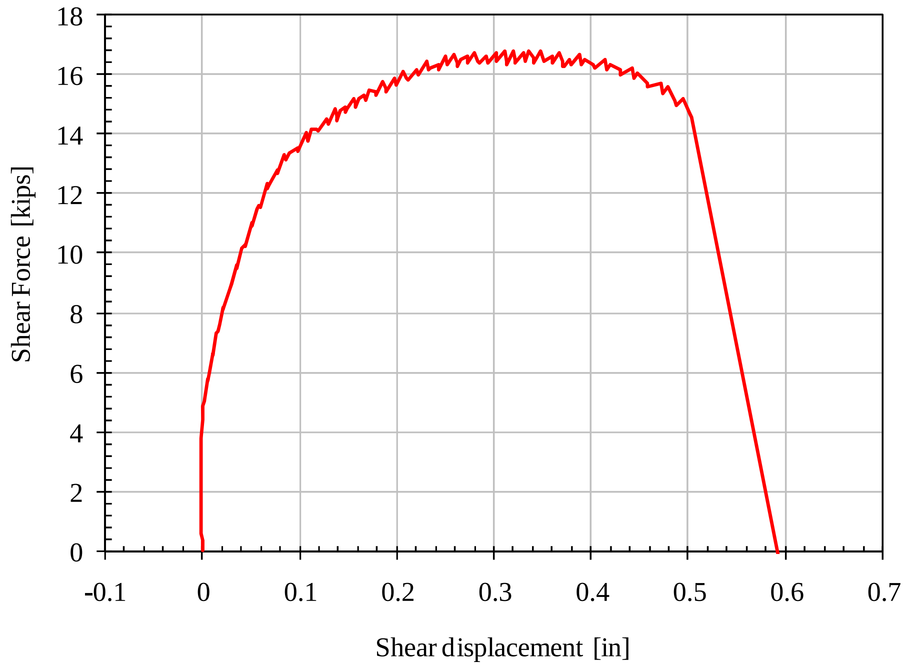
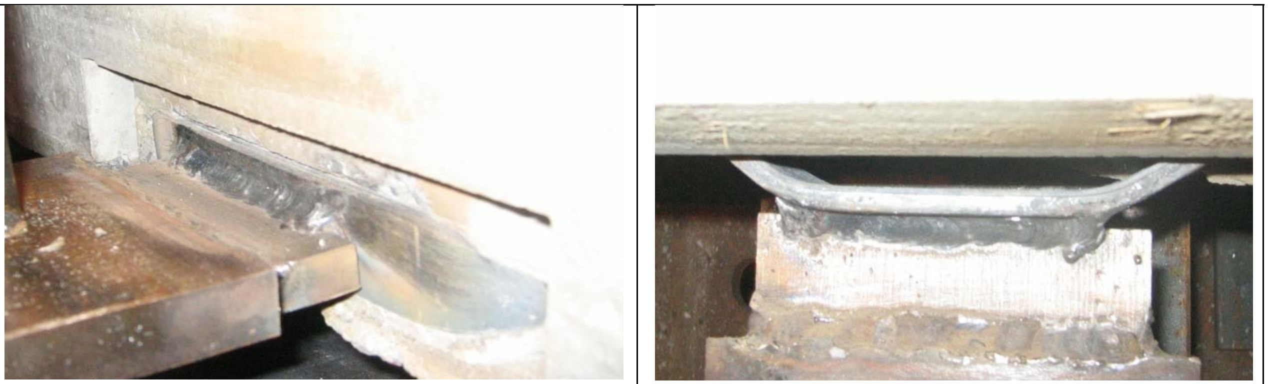


Figure 107: Shear force and displacement (In-plane shear) G2

TEST G3: ASTM A36 CONNECTION UNDER MONOTONIC IN-PLANE TENSION (4-IN PANEL)

The performance of the Universal ASTM A36 connection subject to monotonic, in-plane tension is presented in this section. The connector was subjected to in plane tension displacement with the shear force unrestrained. Connector response was characterized by bending of the faceplate with application of tension. No damage was observed on the concrete surrounding the connection. Loss in capacity occurred due to failure of the faceplate. The observed key events and the corresponding displacement level are presented in Table 62. The photos of the damage states are presented in Figure 108. The final condition of the specimen is presented in Figure 109. The global force deformation response and backbone curve are presented in Table 63 and Figure 110.



a) Initial conditions　　b) 0.62-in.

Figure 108: Damage state at various In-plane tension deformations G3

Figure 109: Final condition of test G3

Table 62: Key Test Observations (In-plane tension) G3		
Event #	Tension Δ Step [in.]	Event Description
1	0.62	Plate bending
2	1.17	Faceplate fractured

Table 63: Experimental Results Backbone Curve (In-plane tension) G3		
Event	Tension Displacement [in.]	Tension Force [kips]
Peak Load	0.59	7.60
End of test	1.23	0

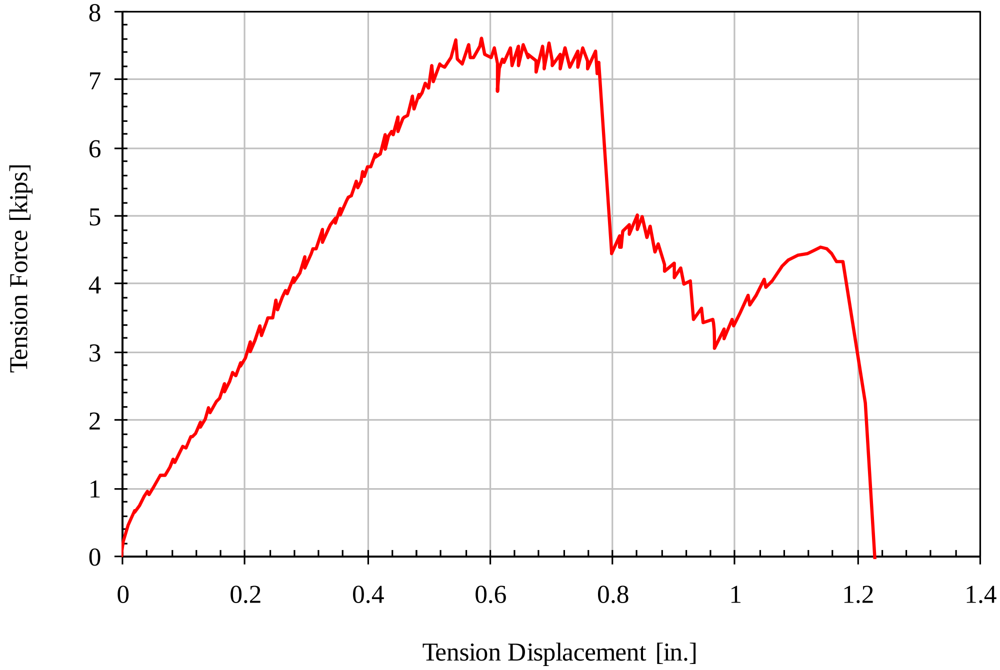


Figure 110: Tension force and displacement (In-plane tension) G3

TEST G4: ASTM A36 CONNECTION UNDER MONOTONIC IN-PLANE TENSION (4-IN PANEL)

The performance of the Universal ASTM A36 connection subject to monotonic, in-plane tension is presented in this section. The connector was subjected to in plane tension displacement with the shear force unrestrained. Connector response was characterized by bending of the faceplate with application of tension. No damage was observed on the concrete surrounding the connection. Loss in capacity occurred due to failure of the faceplate. The observed key events and the corresponding displacement level are presented in Table 64. The photos of the damage states are presented in Figure 111. The final condition of the specimen is presented in Figure 112. The global force deformation response and backbone curve are presented in Table 65 and Figure 113.

a) Initial conditions

b) 0.63-in.

Figure 111: Damage state at various In-plane tension deformations G4

Figure 112: Final condition of test G4

Table 64: Key Test Observations (In-plane tension) G4

Event #	Tension Δ Step [in.]	Event Description
1	0.26	Plate bent
2	0.63	Plate bent and weld tear at both tips
3	1.30	Faceplate completely fractured

Table 65: Experimental Results Backbone Curve (In-plane tension) G4

Event	Tension Displacement [in.]	Tension Force [kips]
Peak Load	0.63	7.21
End of test	1.30	0.47

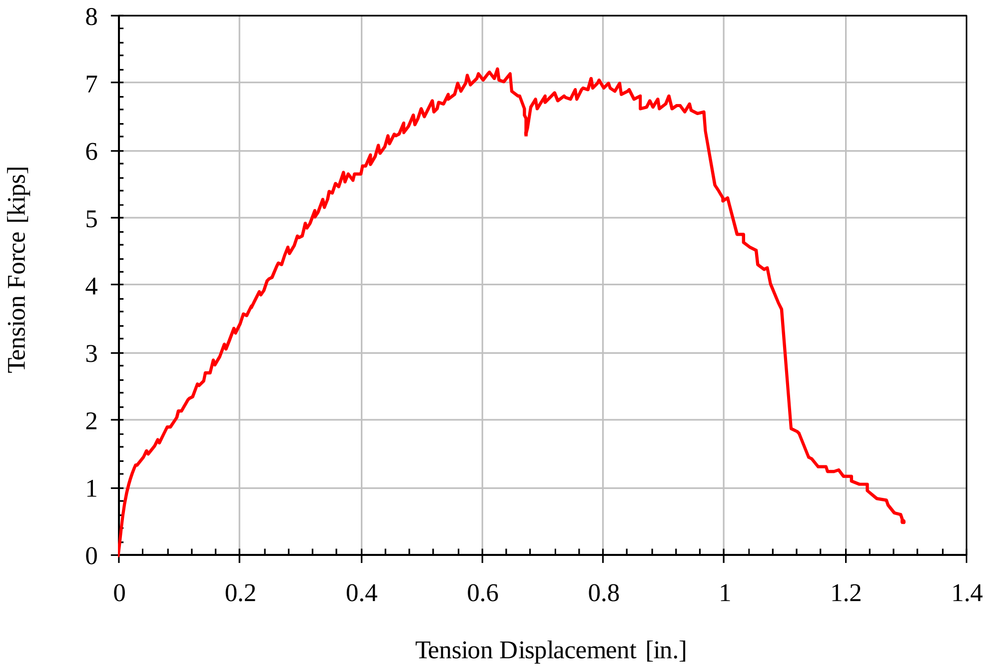
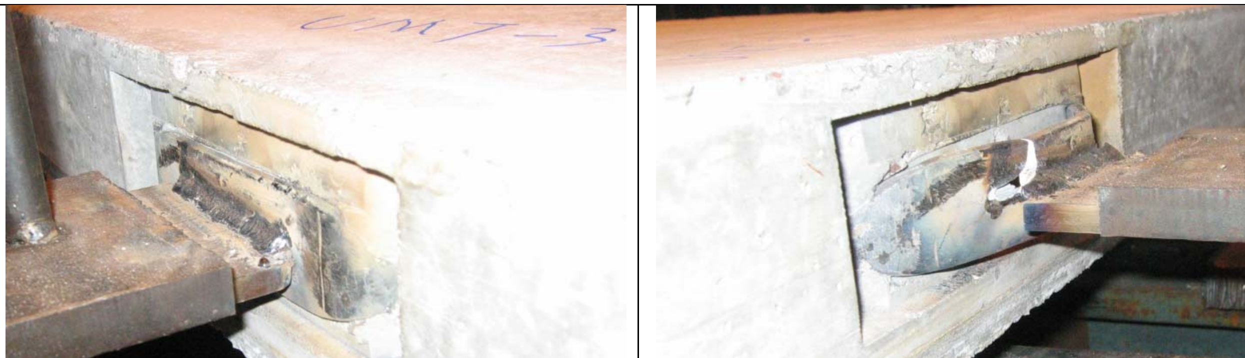


Figure 113: Tension force and displacement (In-plane tension) G4

TEST H3: ASTM A36 CONNECTION UNDER MONOTONIC IN-PLANE TENSION (4-IN PANEL)

The performance of the Universal ASTM A36 connection subject to monotonic, in-plane tension is presented in this section. The connector was subjected to in plane tension displacement with the shear force unrestrained. Connector response was characterized by bending of the faceplate with application of tension. No damage was observed on the concrete surrounding the connection. Loss in capacity occurred due to failure of the faceplate. The observed key events and the corresponding displacement level are presented in Table 66. The photos of the damage states are presented in Figure 114. The final condition of the specimen is presented in Figure 115. The global force deformation response and backbone curve are presented in Table 67 and Figure 116.



a) Initial conditions

b) 0.60-in.

Figure 114: Damage state at various In-plane tension deformations H3

Figure 115: Final condition of test H3

Table 66: Key Test Observations (In-plane tension) H3		
Event #	Tension Δ Step [in.]	Event Description
1	0.26	Plate bent and weld tear at the tip
2	0.60	Faceplate fractured
3	0.93	Faceplate completely fractured

Table 67: Experimental Results Backbone Curve (In-plane tension) H3		
Event	Tension Displacement [in.]	Tension Force [kips]
Peak Load	0.57	11.74
End of test	0.93	1.72

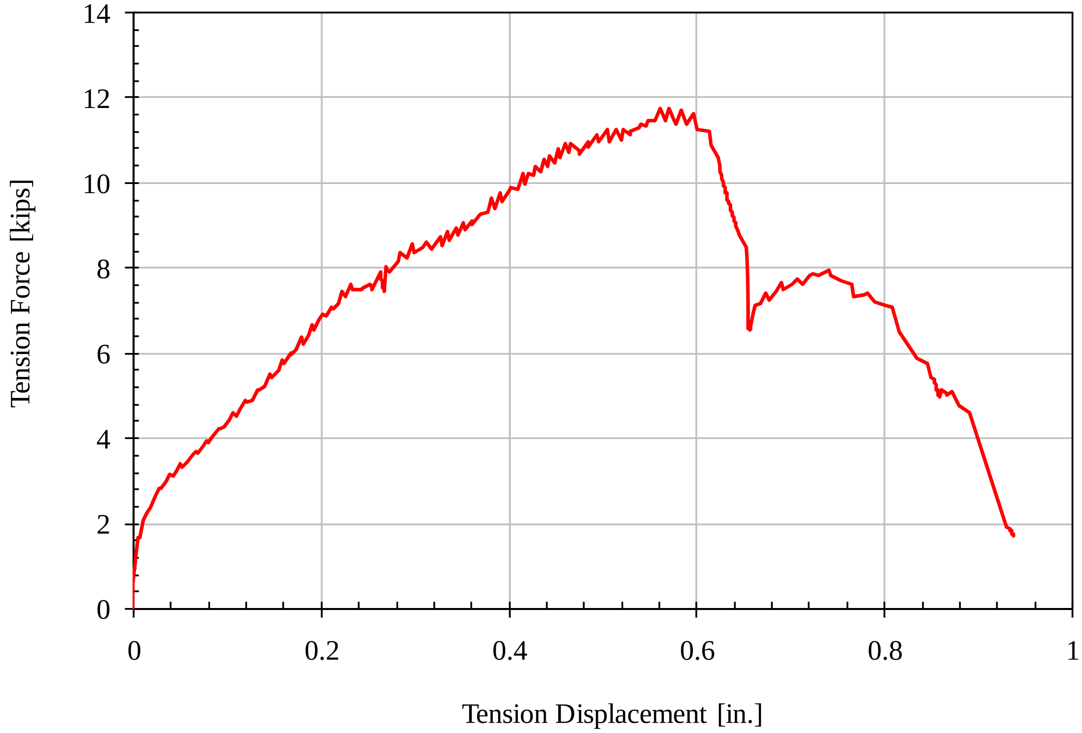


Figure 116: Tension force and displacement (In-plane tension) H3

Test H4: ASTM A36 Connection Under Monotonic In-Plane TENSION (4-in Panel)

The performance of the Universal ASTM A36 connection subject to monotonic, in-plane tension is presented in this section. The connector was subjected to in plane tension displacement with the shear force unrestrained. Connector response was characterized by bending of the faceplate with application of tension. No damage was observed on the concrete surrounding the connection. Loss in capacity occurred due to failure of the faceplate. The observed key events and the corresponding displacement level are presented in Table 68. The photos of the damage states are presented in Figure 117. The final condition of the specimen is presented in Figure 118. The global force deformation response and backbone curve are presented in Table 69 and Figure 119.

a) Initial conditions

b) 0.59-in.

Figure 117: Damage state at various In-plane tension deformations H4

Figure 118: Final condition of test H4

Table 68: Key Test Observations (In-plane tension) H4		
Event #	Tension Δ Step [in.]	Event Description
1	0.59	Plate bent and weld tear at the tip
2	0.85	Faceplate completely fractured

Table 69: Experimental Results Backbone Curve (In-plane tension) H4		
Event	Tension Displacement [in.]	Tension Force [kips]
Peak Load	0.77	12.59
End of test	0.94	0

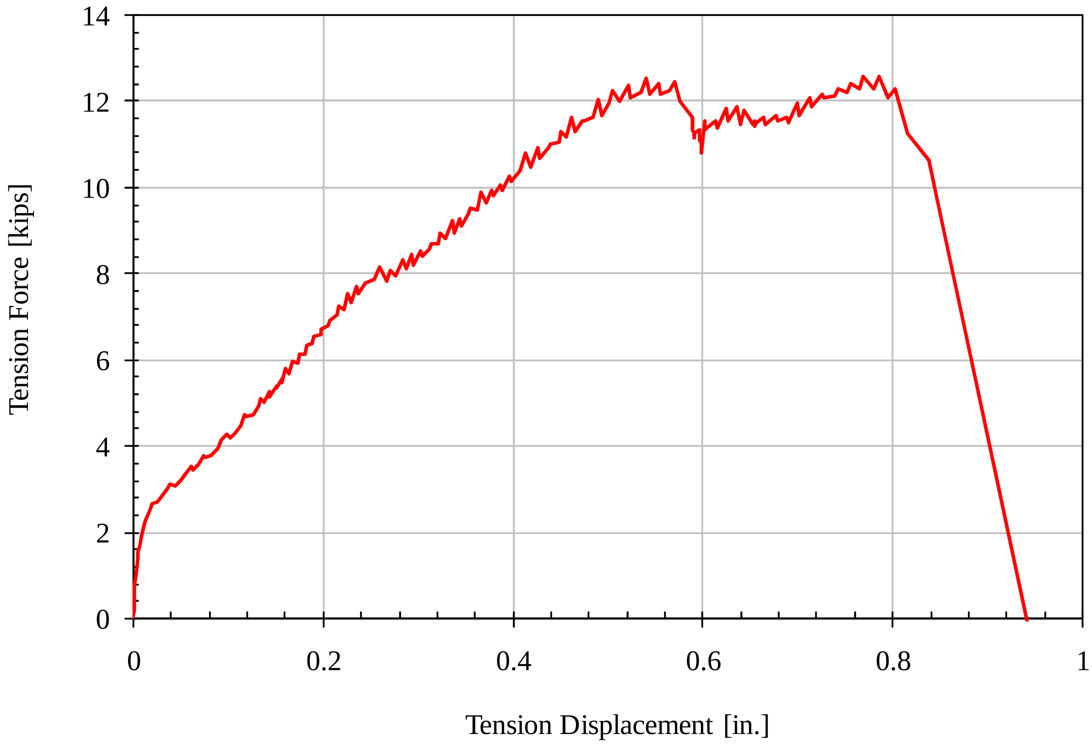


Figure 119: Tension force and displacement (In-plane tension) H4